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Nitrogen storage and variability in paddy soils of China

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Abstract

Paddy soils support important croplands in many parts of the world, especially in Asia. A thorough understanding of nitrogen (N) in Chinese paddy soils would be helpful to comprehend N cycling on farms from a national perspective. The N storage and density of paddy soils in China were evaluated employing 1490 soil profiles and a map of Chinese soils at a scale of 1:1 000 000. Results showed that the mean N density of paddy soils at 0–100 cm was 1240.0 g/m^3, with N storage of 569.0 Tg. Paddy soil N density varies with different soil-water regime. In fact, waterlogged conditions can enhance paddy soil N content. Different rotation systems and various fallow systems also can affect paddy soil N density. There are significant relationships of N between both SOC and sand content. But the sensitivity of paddy soil N to climate was weak because of human activity. While this GIS-based analysis is a relatively coarse evaluation of the database, it does provide the first quantitative assessment of paddy soils N storage across China using commonly available digital databases.

1 Introduction

Nitrogen (N) is a major nutrient for all living things on Earth and plays a central role in regulating the composition, structure, and function of ecosystems (Galloway et al., 2004; Fang et al., 2009; Leip et al., 2008). Nitrogen in terrestrial ecosystems is particularly sensitive to human activities, such as fertilization and cultivation (Zhang et al., 2008; Fang et al., 2008). Enrichment experiments of soil organic carbon (SOC) by Holland et al. (2005) indicate that given the size of SOC, small changes in soil N concentration can transform an ecosystem from a N sink into a source, having profound impacts on global biogeochemical cycling. Because soil N concentration directly influences terrestrial ecosystems, increased N availability increases productivity and biomass accumulation and, at least for the short-term, accelerates the accumulation of SOC (Giardina et al., 2003). Thus, studying the spatial distribution of paddy soil N will enhance our knowledge of its impacts on the environment.

Global soil N storage has been estimated since the 1970s. Early inventories of global soil N used a C/N ratio conversion approach. Nitrogen was calculated from organic carbon storage with a given C/N ratio, and estimated global soil N storage was determined to be 170–550 Pg (Burns and Hardy, 1975; Stevenson, 1982). However, more recently, soil profile measurement approaches have been used to estimate soil N storage. For example, Post et al. (1985) used the Holdridge life zone method and 3100 soil profiles to determine that global N storage to the 1 m depth was 95 Pg. Batjes (1996) used the data from 4353 soil profiles and the 1:500 M FAO-UNESCO Global Soil Map to determine that global N storage to a 1 m depth was 133–140 Pg. Because diverse methods and different data sources can cause variability (Batjes, 2000), no universally recognized global N storage amount has been agreed upon.

Nitrogen storage research in China has been studied at some sites, but only on limited areas in farmland. Ellis et al. (2000) used Monte Carlo uncertainty analysis and soil samples to investigate the N storage in China's Tai Lake Region. They concluded that the N storage of the village soil and sediment has increased from 1930 to 1994 (approximately 25% above the 1930s level). However, changes in paddy soil N storage were nominal. Zhang et al. (2004) reported that the N density of the paddy soil surface (0–20 cm) and profile (0–100 cm) at China's Shenyang Ecology Station experiment area were 1000 g/m^3 and 800 g/m^3, respectively. Tian et al. (2006) estimated the soil N storage in China and investigated the spatial distribution of soil N. As for paddy soils, Tian et al. used the data from 525 soil profiles to obtain the paddy soil area (29.79×10^6 ha) and N storage (273.49–384.23 Tg).

While each of these studies established a foundation for soil N storage of paddy soils in China, most only estimated the N storage and N density, and failed to investigate the factors which affect N storage. Also, previous studies were conducted in limited areas (villages, experimental sub-areas, etc.), or used a finite number of paddy soil profiles. Nationwide estimates of paddy soil N storage had not yet been conducted. Thus, the data from previous research was fraught with uncertainty.

In order to reduce such uncertainty, further research on N storage at the national scale is necessary. This paper employed the newly compiled 1:1 000 000 digital soil map of China (Shi et al., 2004) used in tandem with soil attribute data from 1490 paddy soil profiles. The goals of this study were (1) to estimate N storage and N density in Chinese paddy soils, (2) to characterize the spatial variations of N among paddy soil subgroups and soil regions across China, (3) discuss the impact factors of paddy soils N storage.

2 Data and methods

2.1 Chinese paddy soils

China is a country with a long history of rice production, where the total area of paddy soils is 46 M ha (Liu et al., 2006). As a major cultivated soil in China, paddy soils produce about 30.6% of total grain production (Yu, 2004). With 7000 years of rice cultivation in China, human cultivation has caused different characteristics of paddy soils as the result of frequent water movement. Thus, a unique type of anthropogenic soil is recognized in Chinese soil taxonomy; Chinese paddy soils containing eight subgroups (Li, 1992) (Table 1).

The geographical distribution of paddy soils map of China (1:10 000 000) was used in this study (Li, 1992). The map consists of 8 soil regions, each of which was classified on the basis of environmental factors such as climate, which influence cropping systems (Editorial Board for Physical Geography of China, 1981; Gong et al., 2007). Given that a small number of isolated paddy fields and rice cropping systems are located in North China, only six major paddy soil regions were finally shown in Fig. 1 (Liu et al., 2006).

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2.2 Data source

The data used for this study comes from the second national soil survey of China (National Soil Survey Office, 1993a, 1994a, 1994b, 1995a, 1995b, 1996). This database contains the records of 1490 typical paddy soil profiles across China (Fig. 1). According to technical specification and soil analysis methods of the second national soil survey (Technical Committee of Soil Survey, 1976; Institute of Soil Science, 1978), total N was determined by Kjeldahl digestion, bulk density was determined by soil cylinder with a fixed volume. The Soil Spatial Database was digitized from the 1:1 000 000 Soil Map of China (Shi et al., 2004). Thus, the precision of the database is two orders higher than that of the 1:4 000 000 soil map, which was widely used in previous research studies. The mapping units for paddy soils in the 1:1 000 000 databases are soil families. Correspondingly, 18 162 polygons of paddy soils are identified on the 1:1 000 000 soil map; 75 times more than the 238 polygons found on the 1:4 000 000 soil map. The soil attribute data of 1490 paddy soil profiles was utilized in this study; double the number of soil profiles used in comparable studies. Of the 1490 profiles, 525 are from the Soil Species of China (National Soil Survey Office, 1996). The remaining profiles are from soil survey data of various individual provinces. The Soil Attribute Database includes extensive information such as soil names, profile locations, horizon depth, organic matter, pH, soil texture, etc. Annual rainfall, temperature, and fertilizer rate of each of the soil profiles were also collected. Descriptive statistics of these data are given in Table 2.

2.3 Methods

Using ArcGIS 9.0 (ESRI, 2006), the 1:1 000 000 paddy soil database of China was developed by linking the Soil Attribute Database with the Soil Spatial Database using a pedological professional knowledge-base method (PKB) (Zhao et al., 2006). The depth of paddy soils in China was 94.2±19.5 cm; the typical maximum depth of paddy soils was 150 cm. According to the farming practice in China, surface layer depth is defined as 0–20 cm, and the depth of a profile is defined as 0–100 cm in the present paper. So the total soil N storage of paddy soils was estimated at depths of 0–20 cm and 0–100 cm.

For an individual soil profile with n layers, N density was calculated using Eq. (1):

$$N_j = \frac{\sum_{i=1}^{n} H_i B_i O_i}{\sum_{i=1}^{n} H_i} \tag{1}$$

where, N_j is the N density (g/cm^3) of profile j, H_i is the thickness (cm) of horizon i, B_i is the bulk density (g cm^{-3}) of horizon i, and O_i is the soil total N content (g kg^{-1}) of horizon i.

The N storage of paddy soil was calculated using Eq. (2):

$$\mathrm{TSNS} = \sum_{j=1}^{n} N_j S_j H_j \tag{2}$$

where, TSNS is total N storage of paddy soil (Tg), S_j is the distribution area (ha) of profile j, and H_j is the thickness (cm) of profile j.

The N density of paddy soil was calculated using Eq. (3):

$$\mathrm{TSND}_k = \frac{\mathrm{TSNS}_k}{S_k} \tag{3}$$

where, TSND_k is the total N density (g/m^3) of paddy soil k, TSNS_k is the total N storage (Tg) of paddy soil k, and S_k is the distribution area (ha) of paddy soil k.

Equation (1) was used to first calculate the soil N density of every soil profile. Then Eqs. (2) and (3) were used to calculate the N storage and N density of Chinese paddy soils.

2.4 Statistical analysis

Pearson correlation coefficients were computed to analyze the relationships of total N to SOC, pH, temperature, rainfall, soil texture, and N fertilizer rate. Differences were considered significant at $p<0.05$. Multiple regression analysis was used to estimate the relationship between total N and its impact factors. All statistical analyses were conducted using SPSS 13.0 (SPSS, 2004).

3 Results and discussion

3.1 Total N density and storage of paddy soils in China

Nitrogen density varies substantially in Chinese paddy soils (Fig. 2). Also, small differences exist between the N density distribution patterns of the 0–20 cm and 0–100 cm layers. The 0–100 cm N density is higher in the Southwest region (shown in red), and the N density is lower in South region. The surface N is lower in the middle Sichuan basin and part of Yangtze River region (shown in yellow or dark green).

A 170-fold difference was observed between the highest (1.85×10^4 g/m^3) and lowest (156.0 g/m^3) values of paddy soil N density at the 0–100 cm depth. Total N density in the range of 500–1000, 1000–1500 and 1500–2000 g/m^3 covered 35.2%, 32.8%, 16.9% of the total paddy soil areas in China, respectively. Those with a N density lower than 500 g/m^3 and greater than 2000 g/m^3 covered a limited area of only 6.3% and 8.8%, respectively. The mean N density for the 0–100 cm depth in paddy soils was 1240.0 g/m^3. This was close to Tian's (2006) result of 1274.1±215.9 g/m^3, but was higher than the national mean of 994.0 g/m^3. The N storage for the 0–100 cm depth in paddy soils was 569.0 Tg, which was much higher than Tian's estimate of 273.49–384.23 Tg N in Chinese paddy soils (Tian et al., 2006). Two possibilities help to explain the differences between the studies: 1) in this study, the total area surveyed was 46 Mha, which is about 150% of the area Tian used; 2) the number of soil profiles

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used in our estimation is about three times that used by Tian. Research by Batjes (2000) and Liu et al. (2006) also indicated that diverse methods and different data sources can cause variability.

The mean N density for the 0–20 cm depth in paddy soils was 1870.0 g/m^3. At this depth, the variation in N density was even more pronounced; such that the difference between the highest and lowest N density values was over 170-fold (1.06×10^5 g/m^3 versus 614.0 g/m^3). The total N storage (0–20 cm) of paddy soils amounted to 171.0 Tg. This indicates that a remarkable concentration of total N (30.1%) resides in the surface layer.

3.2 Total N density and storage by paddy soil subgroups

Human cultivation causes frequent water movement in paddy soils and leads to changes in redox potential. Furthermore, distinct material accumulates via eluviation/illuviation, resulting in different characteristics in paddy soils. Thus, surface and sub-surface soil-water regimes directly affect the classification of paddy soil subgroups (Li, 1992; National Soil Survey Office, 1998). Figure 3 shows a fairly substantial variation in N density was found among soil subgroups in China. The highest average N density (1670.0 g/m^3) of 0–100 cm was found in Gleyed paddy soils, while the lowest (571.0 g/m^3) was found in Bleached paddy soils; a two fold difference. In the surface layer (0–20 cm), the average N density of Degleyed and Gleyed paddy soils was high with values of 2010.0 g/m^3 and 1790.0 g/m^3, respectively. By contrast, the average N density of Salinized paddy soils was only 980.0 g/m^3, the lowest among paddy soils subgroups. Also, paddy soil N density varies spatially across the landscape (Fig. 3). Paddy soils located in depressional areas with high underground water levels and poor drainage increase its N density, such as in Gleyed paddy soils. However, Submergenic and Bleached paddy soils, mainly distributed in hill and foothill positions without groundwater interaction, show lower N density at 0–100 cm than other subgroups. This indicates that water saturation can increase paddy soil N density. Bai et al. (2005) also suggested that waterlogged conditions and flooding can enhance total N content in soils. It noteworthy that Salinized and Acid Sulfate paddy soils are also found in depressed areas, but their average N density was much lower than Gleyed paddy soils. This may be due to the fact that these two types of paddy soils are infertile and are mainly found in well drained coastal lands where N leaching occurs.

The Hydromophic, Submergenic, Percogenic and Gleyed paddy soil subgroups account for 92.3% of the total paddy soil area (Table 3). Thus, the N storage (0–100 cm) of these four subgroups account for a large majority of the total N storage of paddy soils in China. Hydromophic paddy soils alone contribute a N storage of 295.0 Tg (51.9% of the total N storage of paddy soil in China). Acid Sulfate paddy soils represent the lowest N storage (1.2 Tg); only 0.2% of the total.

3.3 Total N density by rice cropping system

Paddy soils in China have been divided into six regions (Fig. 1). Each soil region was classified on the basis of climate and cropping system. Figures 2 and 4 show total N density of paddy soil varies with rice cropping system and soil region in China. In the south region, with double or triple rice cropping systems, the paddy soil N density of the surface (1240.0 g/m^3) and profile (850.0 g/m^3) were lower than the average total N density (1460.0 g/m^3 and 960.0 g/m^3, respectively). In the Southwest region, with a single rice cropping system, the N density of the paddy soil surface (0–20 cm) and profile (0–100 cm) were the highest (1950.0 $g/m^3$and 1440.0 g/m^3, respectively).

In Southern China, the Yangtze River and Central regions have the same cropping system and showed no differences in paddy soil N density between the regions. Although the Southwest and North regions also have the same rice cropping system, the Southwest region showed a higher N density than the North (about 430.0 g/m^3 in surface and 470.0 g/m^3 in profile). This is because the Southwest region's paddy soils are usually submerged by water in winter, when wet and warm soil conditions enhance SOC and total N content. The North region's cropping system was fallow in winter, where dry conditions reduce paddy soil N content.

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3.4 Other factors affecting total N density of paddy soils at the national scale

In addition to water condition and cropping system, there are many factors (N fertilizer rate, SOC, pH, climate, soil texture, etc.) which can affect paddy soil N density. Table 4 shows paddy soil N content significantly correlated with SOC, temperature, sand content, and clay content ($p<0.01$). But there are no correlations between total N content and N fertilizer rate. This is likely due to large variations of N fertilizer rate in different paddy fields (the C.V. of N fertilizer rate in different paddy soil profiles was 78.23%), and only a small quantity of N fertilizer (the min value was 1.35 kg ha^{-1} yr) used before 1980.

The relationship of total N to its impact factor was explored through multiple regression analyses. Results show that total N have significant relationship with SOC, temperature, silt content in surface layer (Table 5). In profile layer, total N have significant relationship with SOC and pH, and the R^2 was 0.586. From the equation and R^2 change, we can see the SOC was main impact factor of paddy soils' N variation. This is because the level of total N in soil depends on the balance of inputs and outputs of C and on the C:N ratio, and N is mainly from the decomposition and mineralization of SOC. Other pairs of datasets also have a significant relationship with total N, but most of the R^2 change values were no more than 0.01 (Table 5). Many researchers suggested that soil organic matter and total N have relationships with temperature (Guo et al., 2006; Cookson et al., 2006; Gao et al., 2009). Although the R^2 change of total N and temperature in this study was less than 0.01 (0.002 in the surface layer and 0.000 in profile). But the temperature can explain no more than 51.5% variation of total N in surface layer. It was lower than Yang's results (75.4%) of total N storage in China (Yang et al., 2007). This indicates that human activity in paddy soils (cultivation, irrigation, etc.) decreases the impact of climate on paddy soil total N content.

4 Conclusions

Employing the newly developed Chinese soil map and more soil profiles than previous research, the mean N density at 0–20 cm and 0–100 cm of paddy soils in China were calculated at 1240.0 g/m^3 and 1870.0 g/m^3, respectively. These results were similar to estimates by Tian et al. (2006). However, our estimation of the N storage in the top 1 m of soil was more than 2 times higher than the estimate by Tian et al. (2006). This research covered a larger area (paddy soil area of 46 Mha), used more soil profiles, and higher resolution soil map than previous research. Therefore the reliability of N storage provided by this research is unprecedented for soils in China. Variation of paddy soil N is impacted by many factors at the national scale. Such variation was largely tied to paddy soil subgroup because of water conditions and topographic position. Management decisions over rice cropping systems (rotation systems, fallow systems, etc.) can also affect paddy soil N density. Furthermore, human activities such as cultivation and irrigation weaken the impact of climate on paddy soil N. So, Future studies should focus on the anthropogenic contribution/impact of chemically applied N to Chinese paddy soils.

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Table 1. The subgroups of Chinese paddy soils.

Subgroups[a]	Reference to US Soil Taxonomy[b]	Horizonation[c]	Descriptions
Hydromophic	Inceptisols	Aa-Ap-P-W-G-C	Mainly distributed in floodplain, long cultivation history, well-drained, underground water level was below 90 cm, soil reaction was neutral.
Submergenic	Inceptisols	A-Ap-P-C	Mainly distributed in alluvial plain or low flat ground, moderate drainage, underground water level was below 60 cm, soil reaction was neutral.
Percogenic	Inceptisols	Aa-Ap-C	Mainly distributed on gentle hill slopes, no underground water, associated with rain-fed paddy fields, soil reaction was neutral to slightly acid.
Gleyed	Inceptisols	Aa-Ap-G-C	Mainly distributed in depressional areas, high underground water level, poorly drained, distinct gleyization, soil reaction was slightly acid.
Degleyed	Inceptisols	Aa-Ap-Gw-G	Same distribution area as Gleyed paddy soils, after man-made drainage the underground water level decreases leading to degley processes, soil reaction was slightly acid.
Bleached	Alfisols	A-P-E-C	Mainly distributed in foothills, usually no underground water, impervious layer at 60 cm depth, soil reaction close to neutral or slightly acid.
Salinized	Inceptisols	Aa-Ap-G	Mainly distributed in coastal lands, high underground water level, soil reaction was slightly alkaline.
Acid Sulfate	Inceptisols	Aa-Ap-Ds-G	Mainly distributed in alluvial lands, surface layer is stream sediment, subsoil is acid sulfate soil, soil reaction was acid.

[a] The Soil Classification System of China (National Soil Survey Office, 1998).
[b] According to Cross-reference system between genetic soil classification of China and US Soil Taxonomy (Shi et al., 2006; Soil Survey Staff, 1999).
[c] According to GSCC (Genetic Soil Classification of China), Aa means arable layer, Ap plow pan, C undeveloped parent material, Ds fragmental deposit horizon, E bleached horizon, G gley horizon, Gw degley horizon, P percogenic horizon, W waterlogogenic horizon (Xi, 1994).

Table 2. Descriptive statistics of total N, SOC, pH, soil texture, temperature, rainfall, and N fertilizer rate for 1490 paddy soil profiles across China.

Property	Depth	Min	Max	Mean	S.D.	C.V. (%)
Total N, $g\,kg^{-1}$	0–20 cm	0.09	15.75	1.47	0.66	44.84
	0–100 cm	0.11	11.97	0.91	0.53	58.60
SOC, $g\,kg^{-1}$	0–20 cm	0.13	43.07	2.78	2.08	74.63
	0–100 cm	0.07	28.91	1.68	1.70	100.82
pH	0–20 cm	3.61	9.08	6.43	1.04	16.20
	0–100 cm	3.45	9.59	6.72	0.99	14.69
Bulk density,	0–20 cm	0.79	1.67	1.25	0.14	10.84
g/cm^3	0–100 cm	0.83	1.67	1.41	0.12	8.38
Sand[a], %	0–20 cm	11.97	70.73	35.63	10.21	28.67
	0–100 cm	7.48	71.47	35.15	10.58	30.09
Silt, %	0–20 cm	11.45	66.69	39.82	5.63	14.15
	0–100 cm	10.97	62.11	38.74	5.83	15.04
Clay, %	0–20 cm	0.25	73.92	24.55	10.92	44.47
	0–100 cm	0.06	74.13	26.10	11.53	44.17
Temperature, °C		1.91	25.06	15.93	3.83	24.01
Rainfall, mm		34.58	2600.23	1289.46	349.89	27.13
N fertilizer rate, $kg\,ha^{-1}\,yr$		1.35	275.50	80.41	62.91	78.23

[a] US soil texture classification.

Table 3. Total N storage (Tg) by soil subgroups in China.

Subgroups of Paddy Soil[a]	N[b]	Area (Mha)	N Storage (Tg) 0–20 cm	0–100 cm
Hydromophic	576	23.87	95.3	295.0
Percogenic	174	7.93	25.6	83.5
Submergenic	344	7.11	22.4	82.3
Gleyed	237	3.27	15.0	64.3
Degleyed	56	1.70	7.83	25.5
Bleached	57	1.07	3.01	9.34
Salinized	36	0.64	1.68	7.22
Acid sulfate	10	0.10	0.31	1.20
Total	1490	45.69	171.2	569.0

[a] The Soil Classification System of China (National Soil Survey Office, 1998).
[b] Number of soil profiles.

Table 4. Correlation coefficients between total N, soil organic carbon, pH values, temperature, rainfall, N fertilizer rate, and soil texture for 1490 paddy soil profiles in China.

	SOC	pH	Temp	Rainfall	N fertilizer rate	Soil texture		
						Sand	Silt	Clay
0–20 cm	0.715**[a]	0.048	−0.159**	−0.037	−0.024	−0.204**	0.060	0.160**
0–100 cm	0.763**	−0.009	−0.134**	−0.022	−0.033	−0.166**	0.047	0.129**

[a] Significant correlation at the $p<0.01$ level.

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Table 5. Stepwise multiple regressions results of total N (Y) to its impact factors for paddy soils in China.

Depth	Equation[a]	R^2	R^2 Change	Sig.
0–20 cm	$Y = 0.53 + 0.36 \times SOC$	0.511	0.511	0.000
	$Y = 0.77 + 0.35 \times SOC - 0.01 \times Temp$	0.513	0.002	0.000
	$Y = 0.49 + 0.35 \times SOC - 0.02 \times Temp + 0.01 \times Silt$	0.515	0.002	0.001
0–100 cm	$Y = 0.49 + 0.27 \times SOC$	0.581	0.581	0.000
	$Y = 0.11 + 0.27 \times SOC + 0.06 \times pH$	0.586	0.005	0.000

[a] Using stepwise multiple regression analysis. Factors contain SOC, pH, Temp, Rainfall, and Soil texture, N fertilizer rate, etc.

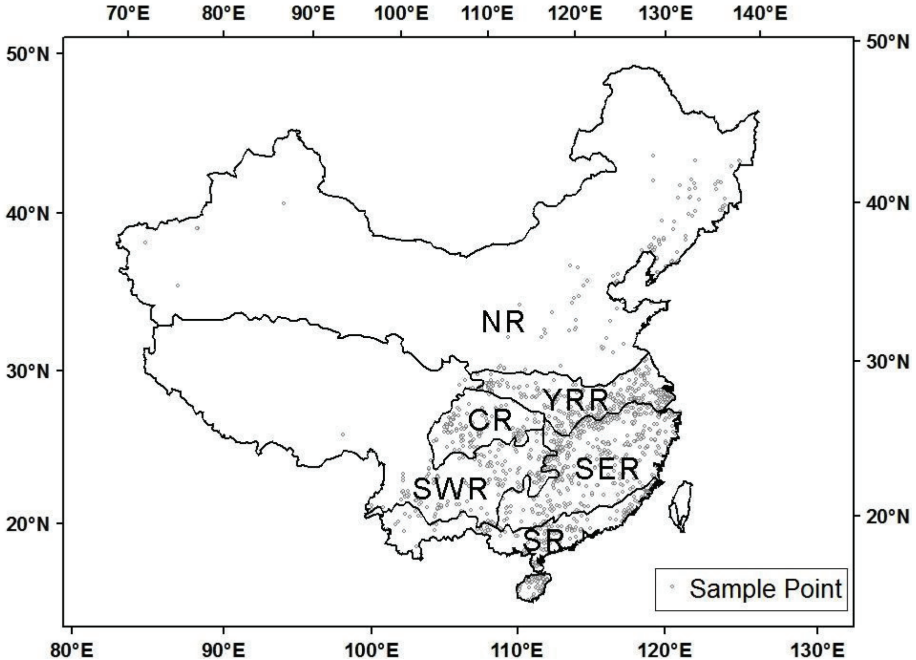

Fig. 1. Location of soil profiles and six paddy soil regions of China. I. South Region (SR): South China double or triple rice cropping region; II. Southeast Region (SER): Southeast China double rice cropping region; III. Yangtze River Region (YRR): Yantgze River paddy-upland rotation (rice-wheat rotation or rice-legume rotation) region; VI. Central Region (CR): Central paddy-upland rotation (rice-wheat rotation or rice-legume rotation) region; V. North Region (NR): North China single rice cropping and winter fallow region; VI. Southwest Region (SWR): Southwest China single rice cropping region.

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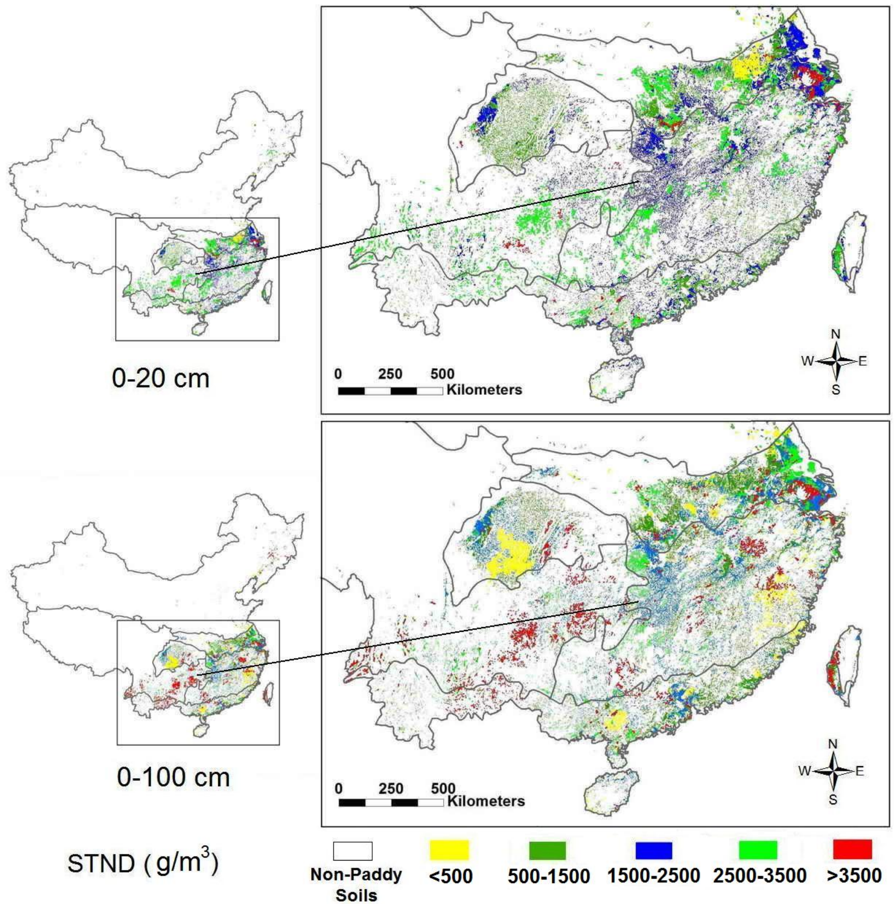

Fig. 2. Distribution pattern of soil total N density (g/m^3) of paddy soils in China.

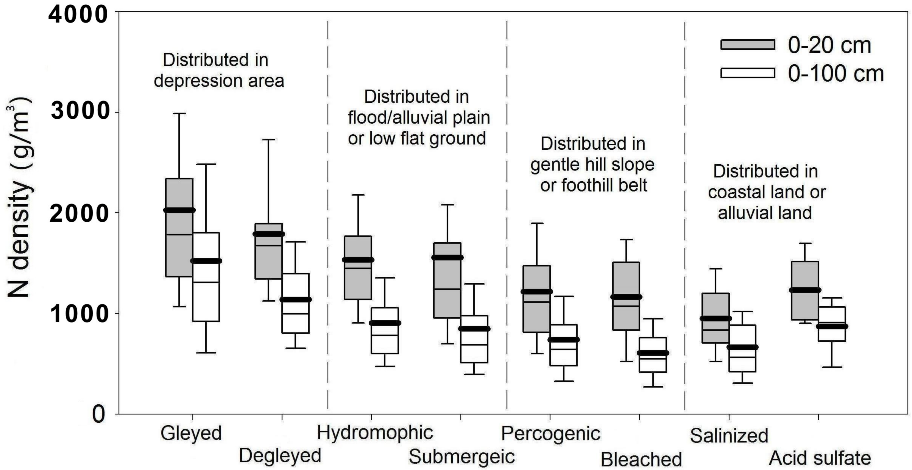

Fig. 3. Nitrogen density (g/m^3) varied in eight subgroups. (Box and whisker plot shows 5th/95th percentile of paddy soil N density and bold black bar represented mean value.)

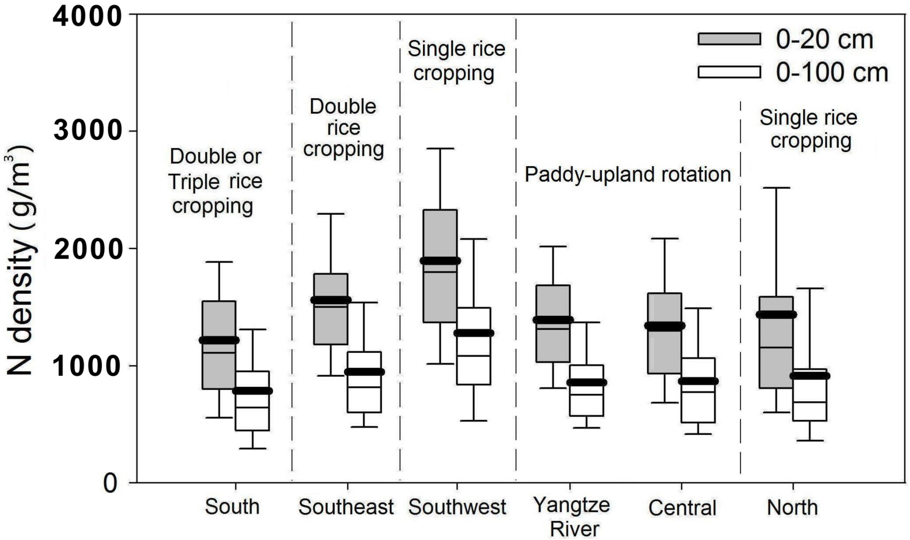

Fig. 4. Paddy soil N density (g/m^3) of six great soil regions in China. (Box and whisker plot shows 5th/95th percentile of paddy soil N density, and bold black bar represented mean value.)