Spatial variability of soil carbon, nitrogen, and phosphorus content and storage in an alpine wetland in the Qinghai–Tibet Plateau, China

Junhong Bai\textsuperscript{A,D}, Hua Ouyang\textsuperscript{B}, Rong Xiao\textsuperscript{A}, Junqin Gao\textsuperscript{C}, Haifeng Gao\textsuperscript{A}, Baoshan Cui\textsuperscript{A}, and Laibin Huang\textsuperscript{A}

\textsuperscript{A}State Key Lab of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, P.R. China.
\textsuperscript{B}Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100010, P.R. China.
\textsuperscript{C}College of Natural Reserve, Beijing Forestry University, Beijing 100083, P.R. China.
\textsuperscript{D}Corresponding author. Email: baijh@126.com

Abstract. This study considers the spatial variability of soil organic carbon, nitrogen, and phosphorus storage in a drained alpine wetland and the possible relationships with soil properties. Top 0–0.30 m soil samples were collected in a typical alpine wetland in the south-eastern Qinghai–Tibet plateau using grid sampling. There was high spatial variability for soil organic carbon density (SOCD), soil total nitrogen density (STND), and soil total phosphorous density (STPD) in the drained alpine wetland. Spherical models best described the structure of the semivariograms for SOCD and STPD, and an exponential model for STND, with the range parameter of <4 m. Similar spatial distribution with lower or higher patches of C, N, and P storage were observed. SOCD, STND, and STPD were significantly negatively correlated with soil moisture ($P<0.01$), and significantly positively correlated with bulk density ($P<0.01$). However, no significant correlations were observed between SOCD, STND, and STPD and soil pH values. Wetland drainage might lead to higher C, N, and P densities in top 0.30 m soils due to peat compaction; thus, it is necessary to incorporate water table fluctuations or the whole depth of peat layers to estimating precisely C, N and P storage.

Additional keywords: drainage, peat soils, Qinghai–Tibet plateau, soil organic carbon, spatial variability, total nitrogen, total phosphorus.

Introduction

Wetland is an important component of the terrestrial ecosystem, and plays a crucial role in modifying regional climate, protecting biodiversity, and sequestrating carbon (C), nitrogen (N), and phosphorus (P) (Howarth \textit{et al.} 1996; Mitsch and Gosselink 2000). Increasing interest has been focused on the role of freshwater wetlands, particularly northern peatlands, as C sinks (White and Reddy 2000; Clair \textit{et al.} 2002; Chmura \textit{et al.} 2003), because these wetlands store about one-third of the global terrestrial soil organic C (SOC) of 1395 Gt (Post \textit{et al.} 2003). Changes in N and P in wetland ecosystems have also been observed, since they are important nutrients for plant growth (Mitsch and Gosselink 2000). However, few studies have been carried out on changes in SOC, N, and P storage in the alpine wetland ecosystems in the Qinghai–Tibet plateau in China, despite their important effects on global changes (Gao 2006) and wetland productivity (Mitsch and Gosselink 2000; Bai \textit{et al.} 2005).

Physical and chemical properties of soils vary spatially due to the nature of soil parent material and soil position in the landscape (Riha \textit{et al.} 1986) and water table fluctuations (Johnston \textit{et al.} 2001). When a soil shifts from saturated to unsaturated conditions, oxidative reactions will be enhanced, resulting in increased soil CO$_2$ emission and decreased N$_2$O or CH$_4$ emissions (Li \textit{et al.} 2004). Lal (2004) suggested that land-use changes (i.e. conversion of natural to agricultural or pasture ecosystems, drainage of wetlands) are among major factors affecting greenhouse gases emissions. It has become clearer that C and N storage in wetlands shows a significant decrease due to the conversion of wetlands to agricultural ecosystems (Lal 2004; Wang \textit{et al.} 2004, 2006; Zhang \textit{et al.} 2008), but that storage will increase with increasing time after abandonment of cultivated wetland (Zhang \textit{et al.} 2007). Additionally, different landscape, land-use (soil management), and hydrological patterns might affect N (Bai \textit{et al.} 2007) and P transfers and forms (Tiessen 1995), which can affect water quality of adjacent rivers or lakes (Mitsch and Gosselink 2000; Bai \textit{et al.} 2007) and possible successional changes (Prusty \textit{et al.} 2009).

Generally, human activity has adversely affected global C, N, and P cycles, and contributed to an alteration of climate that will generate discernible feedbacks to all organisms and ecosystems on the Earth (Mitsch and Gosselink 2000; Wang \textit{et al.} 2006;
He et al. 2008). Therefore, understanding the store and storage potential of C, N, and P helps us understand how ecosystems would respond to natural and anthropogenic disturbances under different management strategies (He et al. 2008). As a result of economic development and population growth, many alpine wetlands were drained and converted to pasture in the Zoige Plateau of China in the late 1970s. The rapid expansion of livestock numbers and drainage of wetlands have caused significant degradation or desertification of alpine wetlands (Bai et al. 2008), accelerating peat decomposition and carbon loss, and sharp decline of wetland biodiversity (Bai et al. 2008), despite some measures (e.g. building natural reserves, banning pasture) to restore and protect these alpine wetlands in the past. However, little information is available on spatial variability of C, N, and P in the alpine wetlands after long-term drainage in this region. Therefore, the primary objectives of this work are: (1) to study the spatial variability of SOC, N, and P storage in a drained alpine peatland; and (2) to reveal the possible relationship between them and other soil properties.

Materials and methods

Study area

The study area is in Hongyuan county in the Zoige plateau, south-east of the Qinghai–Tibet plateau of China (see Fig. 1), 33°10′–34°06′N, 101°36′–103°25′E. Peat soils and alpine meadow soils are widely developed in this region. The Zoige plateau wetland has an important ecological function for retaining water on the upper reach of the Yellow River. This region has a continental humid and semi-humid monsoon climate for an alpine temperature zone, and it is one of the abundant precipitation zones in the Yellow River basin, with annual mean precipitation of 600–800 mm. The dominant plant cover is Carex muliensis community. Hundreds of ditches (~1 m width) have been built in this region since 1970s for drainage of wetlands and grazing. Due to long-term drainage, serious degradation has occurred in these alpine wetlands and Cremanthodium lineare has encroached into the Carex marsh (Fig. 1).

Fig. 1. Locations of sampling sites in the study area.
Soil sampling and analysis

A sampling plot near a ditch (built in 1970s) was selected in Hongyuan county. A 55 by 55 m sampling grid (0.3025 ha) was established as the sampling area. Grid points (i.e. sampling points) were spaced evenly 1 m apart, and 66 grid points were randomly selected. Soil samples were collected from the upper 0.3 m in June 2004. A single 48-mm-diameter soil core was collected from the 0–0.3 m depth within a 0.20-m radius surrounding each grid point, oven-dried at 70°C for 48h, and weighed for bulk density and moisture content determination. Three 20-mm-diameter soil cores were collected from the 0–0.3 m depth within a 0.20-m radius surrounding each grid point and mixed to form a composite sample. All samples were placed in polyethylene bags and brought back to the laboratory. All samples were air-dried at room temperature and sieved through a 2-mm nylon sieve to remove coarse debris and stone. The air-dried soils were then ground with a pestle and mortar for soil chemical analysis. Soil physical and chemical properties are listed in Table 1.

Soil organic matter was determined by the method of Walkley and Black (1934). Soil organic matter was converted to SOC by the Bemmelen index (0.58) because the determination was done by conventional wet combustion with Cr2O7 6− (Wen 1984). Total N (TN) was determined by a modified micro-Kjeldahl digestion procedure. Total phosphorus (TP) was extracted from soils with 1 N HCl after ignition at 550°C (Aspila et al. 1976). Soil pH(H2O) was measured using a pH meter (soil:water 1:5). For quality assurance and quality control throughout the experiments and analyses, all the extracting reagents were prepared using metal-free, AnalaR-grade chemicals. Double-distilled water prepared using quartz double-distillation assembly was used for preparing the reagents (Prusty et al. 2009). All the digestion was conducted in duplicate and each batch included blanks to validate the digestion operation.

We calculated the SOC density (SOCD, kg C/m²), soil total N density (STND, kg N/m²), and soil total P density (STPD, kg P/m²) on a ground-area basis up to 0.3 m depth as follows:

\[
\text{SOCD} = H \times \rho \times \text{SOC} \times (1 - \delta_{2\text{mm}}/100) \times 10^{-1}
\]

\[
\text{STND} = H \times \rho \times \text{TN} \times (1 - \delta_{2\text{mm}}/100) \times 10^{-1}
\]

\[
\text{STPD} = H \times \rho \times \text{TP} \times (1 - \delta_{2\text{mm}}/100) \times 10^{-1}
\]

where H, ρ, and δ2mm are the soil thickness (cm), bulk density (g/cm³), and volumetric percentage, respectively, of the fraction >2 mm (rock fragments); SOC, TN, and TP are contents in mg/kg.

Statistics analysis and mapping

Geostatistical analysis was conducted using GS+ for windows (version 5.1, Gamma Design Software, Plainwell, MI). Only isotropic semivariograms were considered, and semivariance parameters for spherical or exponential models are reported for SOCD, STND, and STPD; and spatial distribution of SOCD, STND, STPD, and soil moisture using Surfer 7.0 (Golden Software, Inc., Golden, CO). Point kriging with no search radius was used as an unbiased, weighted, linear interpolation method that minimises total parameter variance by incorporating semivariogram functions to create contour maps (Isaaks and Srivastava 1989). In addition, Pearson analysis was performed using the SPSS 10.0 statistical package to examine the possible relationship between selected soil properties.

Results and discussion

Mean contents of C, N, and P in drained peat soils

Mean SOC contents were 35.81 ± 3.24% in the drained peat soils (Table 1), which was ~2 times the SOC content in flooded peat soils in this region (Gao 2006). This was in agreement with

<table>
<thead>
<tr>
<th>Soil properties</th>
<th>Mean</th>
<th>s.d.</th>
<th>CV%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOC (%)</td>
<td>35.81</td>
<td>3.24</td>
<td>9.05</td>
</tr>
<tr>
<td>TN (%)</td>
<td>2.35</td>
<td>0.27</td>
<td>11.49</td>
</tr>
<tr>
<td>TP (mg/kg)</td>
<td>996.35</td>
<td>182.87</td>
<td>18.35</td>
</tr>
<tr>
<td>pH</td>
<td>5.22</td>
<td>0.17</td>
<td>3.26</td>
</tr>
<tr>
<td>Water content (%)</td>
<td>78.60</td>
<td>7.56</td>
<td>9.62</td>
</tr>
<tr>
<td>C/N ratio</td>
<td>17.83</td>
<td>2.32</td>
<td>13.01</td>
</tr>
<tr>
<td>Bulk density (g/cm³)</td>
<td>0.58</td>
<td>0.22</td>
<td>37.93</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>17.59</td>
<td>0.64</td>
<td>3.63</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>56.96</td>
<td>2.32</td>
<td>4.07</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>25.45</td>
<td>1.01</td>
<td>3.42</td>
</tr>
</tbody>
</table>

Table 2. Statistical analysis of densities (kg/m²) of soil organic carbon density (SOCD), total nitrogen (STND), and total phosphorus (STPD) in the study area

<table>
<thead>
<tr>
<th>Densities</th>
<th>Mean</th>
<th>s.d.</th>
<th>CV%</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCD</td>
<td>62.01</td>
<td>21.39</td>
<td>34.49</td>
</tr>
<tr>
<td>STND</td>
<td>3.54</td>
<td>1.30</td>
<td>36.72</td>
</tr>
<tr>
<td>STPD</td>
<td>0.17</td>
<td>0.07</td>
<td>41.18</td>
</tr>
</tbody>
</table>

Table 3. Summary of geostatistical parameters for soil densities (kg/m²) of organic carbon (SOCD), total nitrogen (STND), and total phosphorus (STPD) in the drained peatland

<table>
<thead>
<tr>
<th>Model</th>
<th>Nugget (C₀)</th>
<th>Sill (C₀+C)</th>
<th>Range (m)</th>
<th>C₀/(C₀+C)</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOCD</td>
<td>Spherical</td>
<td>0.100</td>
<td>275.5</td>
<td>3.07</td>
<td>0.0004</td>
</tr>
<tr>
<td>STND</td>
<td>Exponential</td>
<td>0.001</td>
<td>1.543</td>
<td>3.48</td>
<td>0.0006</td>
</tr>
<tr>
<td>STPD</td>
<td>Spherical</td>
<td>0.00001</td>
<td>0.00396</td>
<td>3.15</td>
<td>0.0025</td>
</tr>
</tbody>
</table>
the findings of Tong et al. (2005) and Gao (2006) that higher SOC contents occurred in peat soils with lower water contents (<70%) than with higher water contents. This indicates that drainage led to an increase in SOC contents in surface peat soils with certain water contents compared with flooded soils. However, Li et al. (2004) reported that when wetland soils shifted from saturated to unsaturated conditions, the oxidative reactions enhanced SOC loss by CO₂ emission. This was probably related to the fact that peat soils are dominated by incompletely decomposed plant debits or dead roots compared with other wetland soils, and wet conditions with good accretion (e.g. water content 78.60%, elevated bulk density 0.58 ± 0.22 g/cm³; Table 1) could greatly contribute to their decomposition and returning nutrients to soils.

Mean TN content in the drained peat soils was 2.35 ± 0.27%, which was ~4 times higher than in the flooded peat soils in this region (Gao 2006). This could be explained by the fact that drainage or aeration of wetland soils would increase N mineralisation and inorganic-N contents (Olde Venterink et al. 2002). Also, the low C:N ratios in these soils (>20, Table 1) contributed to N mineralisation. Hefting et al. (2004) also found the end product of N mineralisation was nitrate under low water table levels (<–0.30 m), while N loss could only occur by denitrification and leaching due to rainfall events under the above conditions. Bai et al. (2005) stated that water table fluctuations in floodplain wetlands could affect nitrogen transformation and mobility.

With respect to soil P, the mean content (996.35 mg/kg) in drained wetland soils with a narrow soil pH range 5–6 was also higher than in the original wetland soils of this region (741.10 mg/kg; He and Zhao 1999). Richardson (1985) stated that drainage of wet soils decreased plant P availability by Fe–P complexation, particularly in the pH range 4–6. Kang and Freeman (1999) also suggested that water tables might be the dominant controlling factor to regulate the inorganic P concentrations.

Spatial variability of SOCD, STND, and STPD in the drained alpine wetland

Incorporation of bulk density into the value of areal storage results gives a more accurate description of the total mass of soil nutrients within a given area (DeBusk et al. 1994), since soil roots occupy a volume of soil rather than a mass of soil (Johnston et al. 2001). A summary of mean C, N, and P concentrations on the basis of volumetric units in top 0.3 m of peat soils is shown in Table 2. The mean C, N, and P storages were nearly 1 order of magnitude higher in the peat soils studied here than in peat soils of a northern Everglades marsh reported by DeBusk et al. (1994). The spatial variations of SOCD, STND, and STPD were large, with the coefficients of variation (CV) of >30% (Table 2). Although the CV is an index of the overall variation or heterogeneity of a given variable, the statistical analyses could not discern quantitative changes in spatial patterns (Brye et al. 2004). Therefore, the spatial variations of SOCD, STND, and STPD were assessed using geostatistical analysis and kriging techniques.

The range parameters from spherical and exponential semivariogram models for SOCD, STND, and STPD were <4 m, suggesting spatial dependence among sampling points at 1-m spacing and that data were truly independent within the sampling area (Table 3). A spherical model best characterised

![Spatial distribution of soil organic C density (SOCD), total N density (STND), and total P density (STPD) in the study area.](image-url)
the structure of the semivariograms for SOCD and STPD, and an exponential model for STND. Similarly, these models for SOCD, STND, and STPD had small positive nuggets, indicating a positive nugget effect, a sampling error, and/or random and inherent variability of SOCD, STND, or STPD (Liu et al. 2006). Generally, the nugget-to-sill ratio \((C_0/C_0+C)\) can be used to classify the spatial autocorrelation of soil properties. A variable would be considered to have a strong spatial dependence if the ratio is \(\leq25\%\), and have a moderate spatial dependence if the ratio is 25–75%; otherwise, the variable has a weak spatial autocorrelation (Cambardella et al. 1994). In this study, the nugget-to-sill ratios showed strong spatial dependence for SOCD, STND, and STPD \((C_0/C_0+C<0.03;\) Table 3), which might be mainly attributed to the effects of drainage of wetlands. Also, the spatial component \((C/C_0+C)\) in the data nearly completely explained the total variability in SOCD, STND, and STPD. Higher spatial variability could also be observed for SOCD, STND, and STPD in top 0.30 m soils in Fig. 2. Additionally, similar spatial distributions with these patches of lower or higher C, N, and P storage were observed (Fig. 2). Correlation analysis also showed there were significant correlations between SOCD, STND, and STPD \((P<0.01;\) Table 4). Similar trends of enrichment at the eastern part (far from the drained ditch) and upper left corner (near the drained ditch) were observed within this study area. Results showed steep gradients of SOCD, STND, and STPD in the central and south parts along the easting direction.

**Effects of selected soil properties on C, N, and P storage in the drained alpine wetland**

As shown in Figs 2 and 3, the changing trends of SOCD, STND, and STPD were opposite to that of soil moisture, i.e. those patches with higher C, N, and P storage had lower soil moisture. Correlation analysis also showed that SOCD, STND, and STPD were significantly and negatively correlated with soil moisture \((P<0.01)\), while positively correlated with bulk density \((P<0.01)\) (Table 4), which indicated that C, N, and P storage in top 0.30 m soils was lower under unsaturated conditions with higher soil moisture (>70%) due to lower bulk density. However, higher spatial variations of SOCD, STND, STPD, and bulk density were consistently observed in this region (Tables 1 and 2). This was probably related to wetland drainage, since drainage would decrease soil moisture contents and elevate bulk density of soils due to soil compaction. Minkkinen and Laine (1998) also showed the peat layer was decreased by 0.22 m after 60 years of drainage in Finland peatlands. Gao (2006) also reported that the sedimentation rates of peat showed a decrease, from 0.036 g/cm\(^2\).year in 1930s (before drainage) to 0.021 g/cm\(^2\).year in 1980s (after drainage) in this region. Therefore, higher SOCD, STND, and STPD in top 0.30 m soils of drained alpine wetland compared with flooded alpine wetland did not indicate an increase in C, N, and P storage in whole peat layers after drainage. On the contrary, drainage might decrease the total storage of C, N, and P in whole peat layers in this region due to SOM decomposition in surface soils (Gao 2006; Bai et al. 2009). Frolking et al. (2001) also reported that soil moisture was the important factor influencing the balance of the decomposition and accumulation of SOM. Therefore, the elevated bulk density due to drainage could significantly impact C, N, and P storage on a volumetric basis. No significant relationship was observed between C, N, and P contents and soil moisture, despite significant correlations being reported by Tong et al. (2005) and Gao (2006) in peat soils and by Bai et al. (2005) in marsh soils. Although linear or exponential increase in SOC contents with increasing bulk density was reported by Wu et al. (2003), a weak negative correlation was observed.

**Table 4. Correlation coefficients matrix between soil densities of organic carbon (SOCD), total nitrogen (STND), and total phosphorus (STPD) and selected soil properties**

<table>
<thead>
<tr>
<th></th>
<th>SOC</th>
<th>TN</th>
<th>TP</th>
<th>SOCD</th>
<th>STND</th>
<th>STPD</th>
<th>Soil moisture</th>
<th>C/N ratio</th>
<th>Bulk density</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN</td>
<td>0.317*</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TP</td>
<td>0.174</td>
<td>0.155</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOCD</td>
<td>0.091</td>
<td>0.069</td>
<td>−0.045</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STND</td>
<td>−0.062</td>
<td>0.443**</td>
<td>−0.015</td>
<td>0.873**</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>STPD</td>
<td>−0.095</td>
<td>0.059</td>
<td>0.510**</td>
<td>0.781**</td>
<td>0.739**</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil moisture</td>
<td>0.191</td>
<td>0.006</td>
<td>−0.026</td>
<td>−0.748**</td>
<td>−0.715**</td>
<td>−0.705**</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C/N ratio</td>
<td>0.370**</td>
<td>−0.738**</td>
<td>−0.055</td>
<td>0.025</td>
<td>−0.421**</td>
<td>−0.110</td>
<td>0.133</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>BD</td>
<td>−0.228</td>
<td>−0.041</td>
<td>−0.099</td>
<td>0.945**</td>
<td>0.871**</td>
<td>0.796**</td>
<td>−0.795**</td>
<td>−0.085</td>
<td>1.000</td>
</tr>
<tr>
<td>pH</td>
<td>−0.263*</td>
<td>−0.234</td>
<td>−0.316**</td>
<td>0.157</td>
<td>0.109</td>
<td>0.017</td>
<td>−0.273*</td>
<td>0.042</td>
<td>0.230</td>
</tr>
</tbody>
</table>

Fig. 3. Spatial distribution patterns of soil moisture in the study area.
Spatial variability of C, N, and P in an alpine wetland

between SOC and BD in this study. There were significant correlations between TND and TN and C/N ratios. STPD was positively correlated with TP ($P < 0.01$). However, no significant correlations was observed between pH and any of SOCD, STND, or STPD, despite soil pH values being negatively correlated with SOC ($P < 0.05$) and TP ($P < 0.01$) (Table 4).

Conclusions

Higher C, N, and P contents or storage in top 0.30 m peat soils can be observed after drainage. This suggested that water table fluctuation will result in an increase in uncertainty and instability of C sequestration in peatlands based on 0.30 m and 1 m depth soil profiles (Song et al. 2005; He et al. 2008), since there is lower C, N, and P storage at the same soil depths in flooded peatland than drained peatlands. Moreover, there is higher spatial variability at field sampling scale. Spherical models for SOCD and STPD and an exponential model for STND best characterised the structure of their semivariograms. Therefore, it is necessary to classify peatlands into such subcategories as flooded, seasonally flooded, and non-flooded and to sample intensively for precisely estimating C storage at regional or global scales. Soil fertility assessment and wetland management also require finer detail and greater certainty about soil spatial variability through on-site, intensive sampling than is provided by soil surveys (Gaston et al. 2001; Bai et al. 2005). The uncertainty of estimating C, N, and P storage will be greatly reduced as result of incorporating the whole thickness of peat layers developed on the parent materials. Additionally, drainage of wetlands will increase the potential emission of CO$_2$ due to SOM decomposition. Some steps have been taken to restore hydrological conditions in these drained alpine wetlands in the Zoige plateau; this will reduce potential C loss and help to alleviate global warming.

Acknowledgements

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