Junhong Bai[1]
Junjing Wang[1]
Denghua Yan[2,*]
Haifeng Gao[1]
Rong Xiao[1]
Hongbo Shao[3]
Qiuyi Ding[1]

[1]State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing, P. R. China
[2]Department of Water Resources, Institute of Water Resources and Hydropower Research, Beijing, P. R. China
[3]Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai, P. R. China

Research Article

Spatial and Temporal Distributions of Soil Organic Carbon and Total Nitrogen in Two Marsh Wetlands with Different Flooding Frequencies of the Yellow River Delta, China

A field study was carried out in two typical marsh wetlands (Sites A and B) with different flooding frequencies in the Yellow River Delta of China in three different dates to investigate spatial and temporal distributions of soil organic carbon (SOC) and total nitrogen (TN) along the distance away from one tidal creek and the Yellow River, respectively. The results showed that SOC and TN contents and densities generally decreased with depth, except for an obvious accumulation peak of TN at the 20–40 cm soil layer; and they had higher heterogeneity at both Sites A and B; However, SOC and TN contents and densities showed different spatial distribution patterns at both sites in different sampling dates. Generally, SOC and TN contents in marsh soils were higher at Site A than those at Site B. TN was significantly correlated with available phosphorous, SOC, and the carbon/nitrogen (C/N) ratio at both sites, whereas SOC was significantly correlated with soil depth, soil moisture and salinity at both sites. Additionally, the C/N ratios were higher at Site B than those at Site A, and they were significantly correlated with soil moisture (Site A), bulk density, and TN (Sites A and B).

Keywords: Biogeochemical cycle; C/N ratio; Ecosystem; Horizontal distribution; Profile distribution

Received: January 30, 2012; *revised:* March 14, 2012; *accepted:* March 31, 2012

DOI: 10.1002/clen.201200059

1 Introduction

Wetlands are one of the most valuable ecosystems and play a crucial role in adjusting global biogeochemical cycles of carbon and nitrogen and protecting water quality of rivers [1, 2], since wetland soils serve as "sink", "source", and "transfer" of these nutrients [2]. It has been proved that wetlands are the largest component of biological carbon pool and thus the increasing studies have focused on carbon cycles in wetland ecosystem. The future sea-level rise can inundate a lot of coastal wetlands and change wetland patterns [3, 4], which might lead to a great potential changes in carbon and nitrogen content and stock [2, 5, 6]. Many researchers have reported that changes in wetland hydrology (i.e., river discharge, season flow, and tidal flow) can greatly influence nutrient (i.e., C and N) forms, transformation, and their distributions in marsh soils [7–10]. Moreover, Hughes [11] and Bai et al. [9, 10] found that the flooding duration and frequencies could influence soil nutrient distribution. Floods are responsible for the variation in soil nutrient distributions due to flood pulses [9]. Therefore, understanding spatial distributions of carbon and nitrogen stocks in salt marsh soils as affected by hydrological fluctuation is crucial to accurately assess coastal wetland soil quality and their contributions to global biogeochemical cycles of carbon and nitrogen.

Correspondence: Dr. J. Bai, State Key Laboratory of Water Environment Simulation, School of Environment, Beijing Normal University, Beijing 100875, P. R. China
E-mail: junhongbai@163.com

Abbreviations: Bd, bulk density; **C/N**, carbon/nitrogen; **SOC**, soil organic carbon; **SOM**, soil organic matter; **TN**, total nitrogen

Wetlands are characterized by high hydrologic flux and nutrient concentrations, rich biodiversity and high productivity [12, 13]. Variations in C and N in marsh soils can greatly influence marsh wetland productivity since both C and N are essential components of aquatic vegetation [14]. Meanwhile, plant litter inputs are one of important sources of C and N in marsh wetland soils. However, soil organic matter (SOM) decomposition processes will be controlled by hydrological conditions (i.e., flooding frequencies) of marsh wetlands, thus impact C and N cycles in marsh soils [8, 9]. Although the increasing studies have focused on the spatial distribution of soil nutrient contents in wetland soils, less is known about the spatial and temporal pattern of soil organic carbon (SOC) and total nitrogen (TN) content and storage in salt marshes with different flooding frequencies.

The primary objective of this study was to investigate the vertical and horizontal distributions of SOC and TN content and storage in two salt marshes with different flooding frequencies in three sampling dates and to reveal the relationships between SOC and TN and other soil properties.

2 Materials and methods

2.1 Site description

The Yellow River Delta is located on the west coast of Bohai Sea (Fig. 1), and it is one of the most complete, extensive, and youngest

*Additional correspondence: Dr. D. Yan, Institute of Water Resources and Hydropower Research, Beijing 100038, P. R. China.

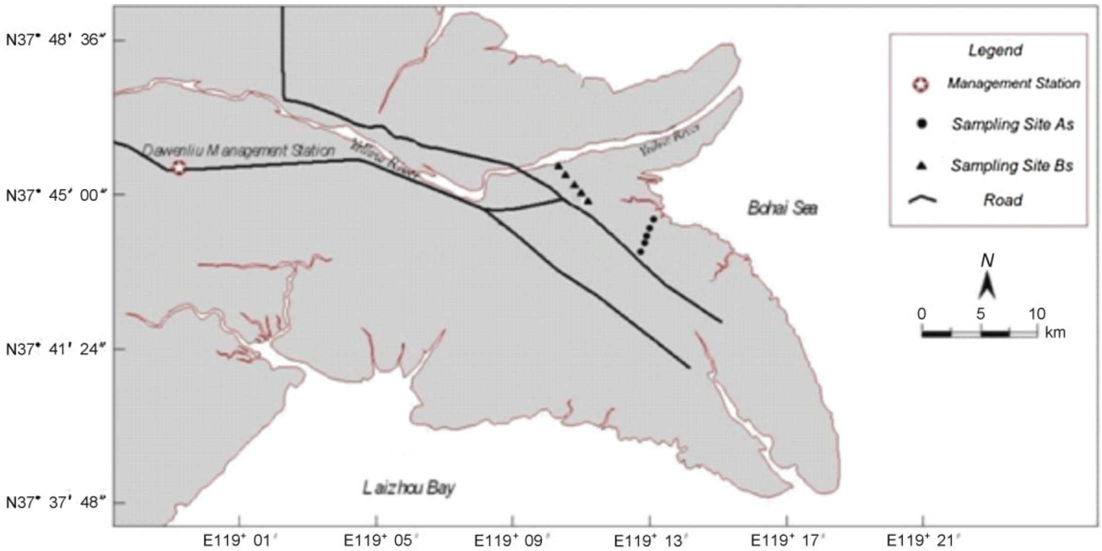

Figure 1. Location map of sampling sites at both sites in the Yellow River Delta.

regions of salt marsh wetland ecosystem among the worldwide larger river deltas. It has a semi-humid continental monsoon climate with distinct four seasons and contemporary conditions for rain and heat. The annual average temperature is 12.3°C and the annual average sunshine hour varies from 2590 to 2830 h. The annual average precipitation ranges from 530 to 630 mm and the rainfall mainly concentrates in summer which often leads to the summer flooding or shot-term flooding in this region and the outlet discharged flow and sediment from the upstream Xiaolangdi Reservoir of the Yellow River. The perennial flooding area covers approximately 211×10^5 hm^2, accounting for more than 63% of total wetland area of this region [15]. The annual mean ratio of evaporation to precipitation can be up to 3.40, and the highest value (7.54) appears in spring, which often causes serious drought disaster [11]. The soil type is dominantly coastal saline soil. The dominate vegetation in tidal wetlands include the herbaceous plants (*Phragmites australis* and *Suaeda salsa*) and the shrub (*Tamarix chinensis*).

2.2 Sample collection and analysis

Two typical marsh wetlands with different flooding frequencies were selected in the Yellow River Delta. Five sampling plots were selected along a 350-m length of sampling zone perpendicular to a tidal creek in the tidal flooding wetland (Site A) and five sampling plots along a 350-m length of sampling zone perpendicular to the Yellow River channel in short-term flooding zones (Site B, only flooded by overbank flow for a short time after the water and sediment regulation regime of the upstream Xiaolangdi Reservoir) in three dates (i.e., September and November of 2007 and April of 2008) (Fig. 1). Soil profiles were collected and stratified at depths of 0–10, 10–20, 20–40, and 40–60 cm at both Sites A and B. A total of 120 soil samples were obtained. All soil samples were placed in polyethylene bags and brought to the laboratory at once. About one third of fresh soils were stored at 2°C to determine mineral nitrogen (NH_4^+–N and NO_3^-–N). All sub-samples were air dried at room temperature for 3 wk. Recognizable plant litters, coarse root materials and the stone were removed from air-dried soils. All air-dried soils were ground using a pestle and mortar until all passed a 0.18-mm nylon sieve, mixed well and stored in covered cardboard containers for the determination of soil chemical properties. Additionally, a single 4.8-cm diameter soil core was collected from each site for the determination of bulk density (Bd) and soil moisture. TN and total carbon was measured using the Elemental Analyzer (Vario EI, Elementar Co., Germany); nitrate nitrogen (NO_3^-–N) and ammonium nitrogen (NH_4^+–N) were measured in 2 M KCl extracts using the automated flow injection analysis AA3 (Bran + Luebbe GmbH, Germany); for analysis of total phosphorous (TP), soil samples were digested by $HClO_4$–HNO_3–HF mixture in Teflon tubes. The solution of the digested samples was analyzed by inductively coupled plasma atomic absorption spectrometry (ICP/AES). The available phosphorous (AP) was extracted using 0.5 M sodium bicarbonate, as described by Olsen et al. [16]. Soil pH and salinity were measured in the supernatant of 1:5 soil–water mixtures using a Hach pH meter (Hach Company, Loveland, CO, USA) and a salinity meter (VWR Scientific, West Chester, Pennsylvania, USA), respectively. SOM was measured using dichromate oxidation [17] and then was transformed to SOC by multiplying the Bemmelen index (0.58). SOC and TN densities at certain layers of each sampling site were calculated by the following equations:

$$\mathrm{SOCD} = \sum B_\mathrm{i} \times \mathrm{SOC_i} \times T_\mathrm{i} \tag{1}$$

$$\mathrm{TND} = \sum B_\mathrm{i} \times \mathrm{TN_i} \times T_\mathrm{i} \tag{2}$$

where SOCD and TND are SOC density and TN density, respectively (i.e., SOC or TN storage in unit area (kg C/m^2)); B_i is the soil Bd (g/cm^3); T_i is the thickness of soil layer i (cm); $\mathrm{SOC_i}$ and $\mathrm{TN_i}$ are SOC and TN contents at soil layer i ($i = 1, 2, 3, 4$), respectively.

2.3 Statistical analysis and graphing

Person correlation analysis was performed to identify the relationship between TN, SOC and selected soil properties. One-way ANOVA analysis was conducted to reveal the differences of soil properties between tidal flooding and short-term flooding wetlands and the differences were considered significant if $p < 0.05$. Statistical analysis was conducted using SPSS 16.0 software package. The linear graphs and counter maps were performed using Origin 8.0 and surfer 10.0 software packages, respectively. Kriging was used as an unbiased weighted linear interpolation method to conduct counter maps.

3 Results and discussion

3.1 SOC content and density in two marsh wetlands

3.1.1 Dynamic changes of the average SOC content and density with depth

The average SOC content generally decreased with depth along a 40 cm depth profile at Sites A and B in the Yellow River Delta in three sampling dates, except for a slight increase in bottom soils at Site B (Fig. 2). This was consistent with the result reported by Bai et al. [11] in their studies on SOM distribution in a river marginal wetland. Franzluebbers and Stuedemann [18] and Hiederer [19] also reported that SOC contents decreased with depth in other ecosystems. The aboveground and belowground biomass of plants might dominantly control the profile distribution of SOC. The higher aboveground allocation of *P. australis* at both sites and the decomposition of plant litters contributed to SOC accumulation in surface soils [20, 21]. Moreover, root biomass mainly distributed in the top 30 cm soils [11], which could improve SOC contents in the top soils through root-decay process [22].

The average SOC level sharply decreased with depth along soil profiles at Site B, whereas it showed a slight decrease at Site A. This might be ascribed to the variability of soil erosion in different soil profiles [23] and stronger sedimentation processes at Site A as affected by tidal seawater flows or freshwater flows controlled by the water and sediment regulation regime of the Xiaolangdi Reservoir. Lowery et al. [24] found that elevated carbon contents were associated with increasing soil erosion in eroded Dubuque soil. Moreover, dissolved organic carbon could move downward through leaching [10] and thus result in the relative homogeneous profile distribution of SOC at Site B due to short-term flooding. The average SOC level in September of 2007 was lower than that in another two sampling dates at Site A, whereas it was opposite at Site B. The potential explanation for lower SOC level in September at Site A was due to higher SOM accumulation in cold climate (i.e., November and April) than in warmer season (i.e., September). However, at Site B, the higher SOC level in September might be associated with the organic matter inputs of overbank flows since they can bring more nutrients to soil [11], while SOC loss could occur with alternative drying and wetting conditions in other sampling dates. Wu [25] also reported that SOC contents were strongly controlled by the hydrothermal conditions. We also observed the significant correlations between SOC contents and soil moistures at both sites ($p < 0.01$; Tabs. 1 and 2).

The average SOCD values showed opposite distribution tendency to that of SOC, and higher SOCD appeared in deeper soils of both Sites A and B in three sampling dates (Fig. 3). The highest SOCD appeared at the soil depth of 60 cm, except for the highest value at the soil depth of 40 cm at Site B in September of 2007. Higher soil Bd in deeper soils could explain the higher SOCD in deeper soils with lower SOC level [26]. Compared to another two sampling dates, higher SOCD was observed in November of 2007 at all soil layers of Site A. This might be ascribed to the fact that cold climate could contribute to SOC accumulation [26]. Wu [25] also found that SOCD might be greatly influenced by temperature and different moisture.

3.1.2 Spatial and temporal distribution pattern of SOC content and density

Figure 3 shows spatial distributions of SOC and SOCD levels in different sampling dates using Kriging method. A graded tone scheme legend to the contents was used to show SOC and SOCD levels. Higher SOC contents were generally observed at Site A than those at Site B, which might be associated with tidal water inputs. However, Site B had similar spatial distribution pattern to Site A in

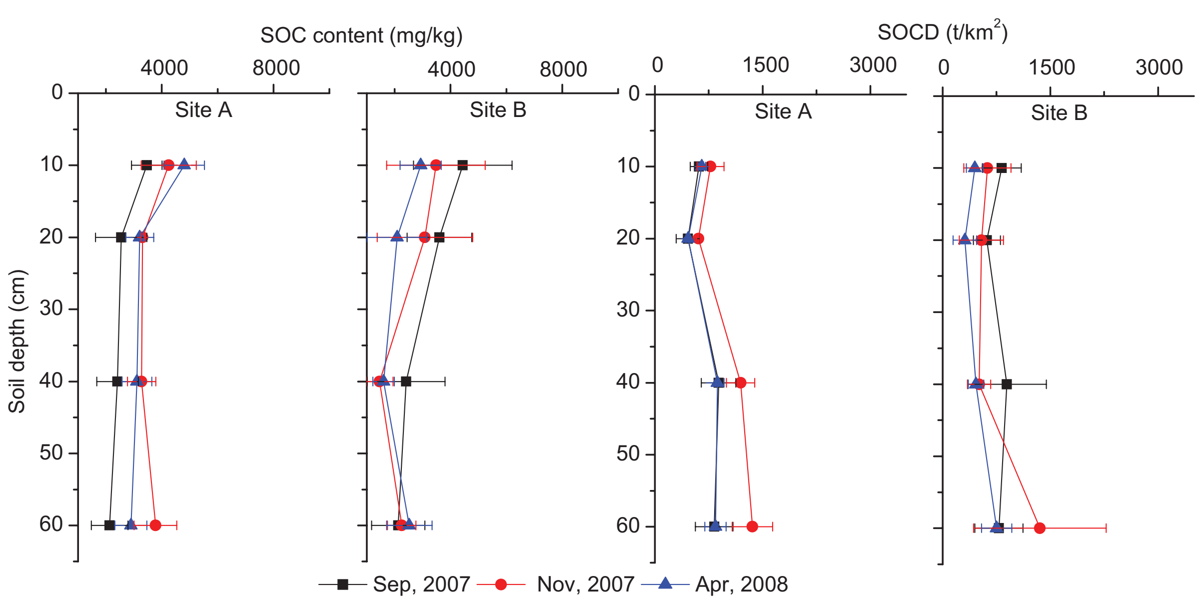

Figure 2. Profile distributions of the average SOC and SOCD in the tidal flooding wetland (Site A) and short-term flooding wetland (Site B) of the Yellow River Delta in three sampling dates.

Table 1. Correlation coefficient matrix of TN and SOC and other selected soil properties for all sampled soils at Site A

	Depth	Moisture	Bd	pH	Salinity	NH_4^+–N	NO_3^-–N	TN	AP	TP	SOC	C/N
Depth	1.000											
Moisture	−0.243	1.000										
Bd	0.163	−0.345*	1.000									
pH	0.249	−0.309*	0.652**	1.000								
Salinity	−0.162	0.333*	−0.729**	−0.464**	1.000							
NH_4^+–N	−0.540**	0.358*	−0.428**	−0.221	0.327*	1.000						
NO_3^-–N	−0.080	0.167	0.626**	0.364*	−0.384*	0.047	1.000					
TN	−0.474**	0.575**	−0.591**	−0.402**	0.559**	0.519**	−0.017	1.000				
AP	−0.063	0.369*	−0.329*	−0.347*	0.108	0.146	−0.063	0.341*	1.000			
TP	−0.248	0.227	−0.008	0.137	−0.069	−0.148	0.113	0.321*	0.013	1.000		
SOC	−0.462**	0.435**	−0.390**	−0.256	0.320*	0.363*	−0.236	0.582**	0.204	0.124	1.000	
C/N	0.144	−0.316*	0.330*	0.245	−0.288	−0.271	−0.080	−0.713**	−0.405**	−0.271	0.001	1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

Table 2. Correlation coefficient matrix of TN and SOC and other selected soil properties for all sampled soils at Site B

	Depth	Moisture	Bd	pH	Salinity	NH_4^+–N	NO_3^-–N	TN	AP	TP	SOC	C/N
Depth	1.000											
Moisture	0.136	1.000										
Bd	0.098	0.053	1.000									
pH	0.313*	−0.158	−0.367*	1.000								
Salinity	−0.264	0.195	0.220	−0.202	1.000							
NH_4^+–N	−0.152	0.078	−0.036	0.158	−0.019	1.000						
NO_3^-–N	−0.416**	−0.036	−0.037	0.043	0.280	0.054	1.000					
TN	−0.221	0.134	−0.217	0.091	0.189	−0.069	0.315*	1.000				
AP	−0.272	0.254	−0.103	−0.133	0.120	0.102	0.365*	0.421**	1.000			
TP	−0.260	0.165	−0.044	−0.106	0.101	0.157	−0.017	−0.052	0.047	1.000		
SOC	−0.411**	0.291*	0.127	−0.055	0.345*	0.220	0.459**	0.586**	0.576**	−0.094	1.000	
C/N	−0.033	0.006	0.321*	−0.195	0.161	0.066	0.066	−0.627**	−0.095	−0.066	0.021	1.000

* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

September, showing that SOC levels increased in deeper soils with increasing distances away from the tidal creek or the Yellow River channel. Moreover, higher SOC levels in bottom soils (40–60 cm) and lower SOC levels in upper soils were observed at the distance of 350 m at both sites in November and April. Hill and Cardaci [27] also reported that organic carbon amounts in deeper soils was significantly greater than those in surface soils. This might be caused by leaching of dissolvable organic carbon and the consumption of the denitrifiers in different soil layers along soil profiles [21, 28]. The obvious patches with higher or lower SOC contents indicated higher spatial variabilities of SOC in November and April at Site A and in September and November at Site B. Additionally, an obvious accumulation patch of SOC content appeared in surface soils at the distance of 0 m (Site B) and 100 m (Site A) of sampling zones in November. Spatial variability of landform and soil hydrology in sampling zones at a small scale could be the potential explanation [11].

As shown in Fig. 3, higher SOCDs were observed in upper soils than in deeper soils at both sites in three sampling dates. Moreover, SOCDs, especially in November, were obviously higher at Site A compared to Site B. This was associated with higher SOC content at Site A. The patches with higher SOCD appeared in upper soils at the distance of 350 m away from the tidal creek at Site A. However, except for similar distribution in November, higher SOCD appeared in upper soils at the distance of 0 m away from the Yellow River channel at Site B in September and April. The higher Bds of these soils made up for lower SOC contents, while the lower Bds decreased the values of SOCD [26]. Generally, spatial variability of SOCD was lower than those of SOC in the study area.

3.2 TN content and density in two marsh wetlands

3.2.1 Dynamic changes of the average TN content and density with depth in two marsh wetlands

Figure 4 shows profile distribution of TN content and density in two marsh wetlands in three sampling dates. The average TN content gradually decreased with depth except for an obvious accumulation peak at the 20–40 cm depth of both sites. However, Bai et al. [11] reported that TN content decreased with increasing soil depth in a river marginal wetland. This might be caused by the leaching of dissolved organic nitrogen [10] and nitrate nitrogen (1.68 ± 0.41 mg/kg at the 20–40 cm depth in this study). The average TN contents were higher in September and April than those in November. The inputs and decomposition of plant litters in warmer seasons could contribute to TN accumulation in surface soils [29]. Moreover, nitrogen inputs of wet deposit (i.e., snow) in winter would lead to higher TN contents in April. As shown in Fig. 2, the changing tendency of

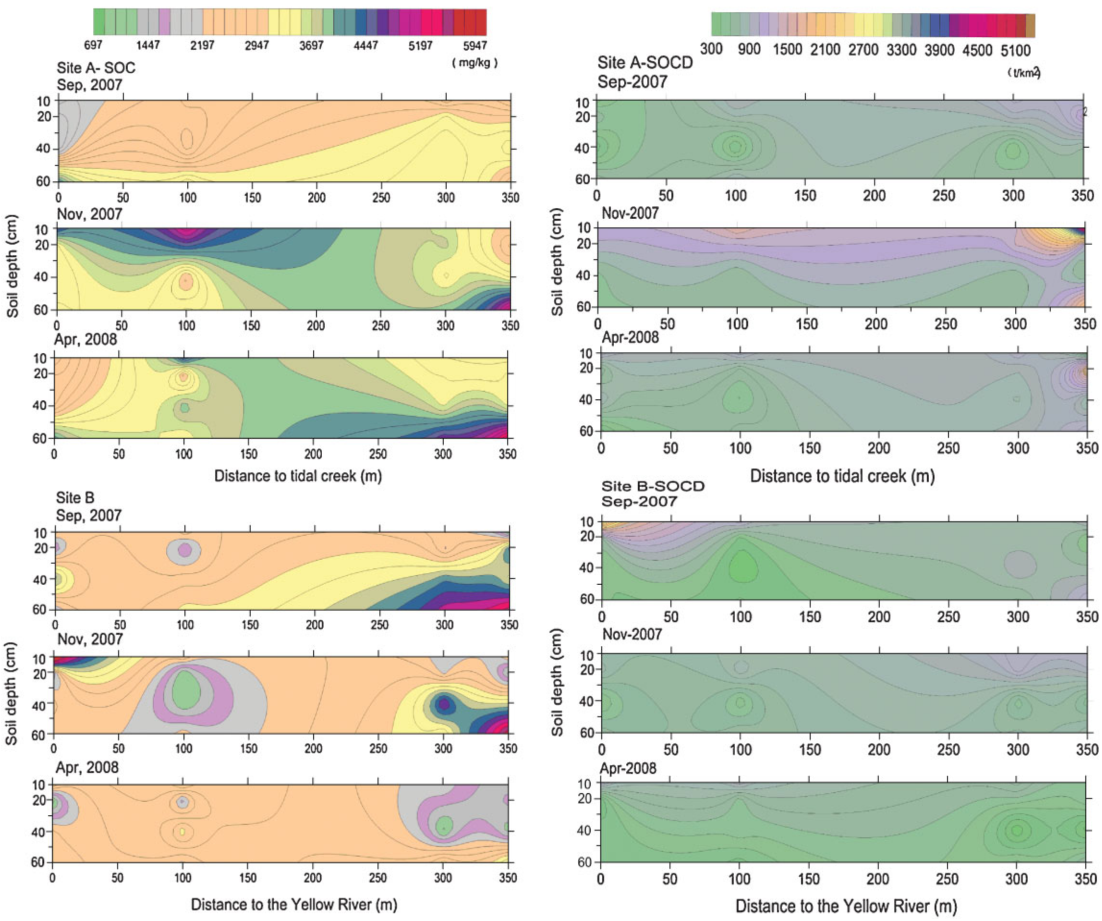

Figure 3. Spatial and temporal distributions of SOC and SOCD in the tidal flooding wetland (Site A) and short-term flooding wetland (Site B) of the Yellow River Delta in three sampling dates.

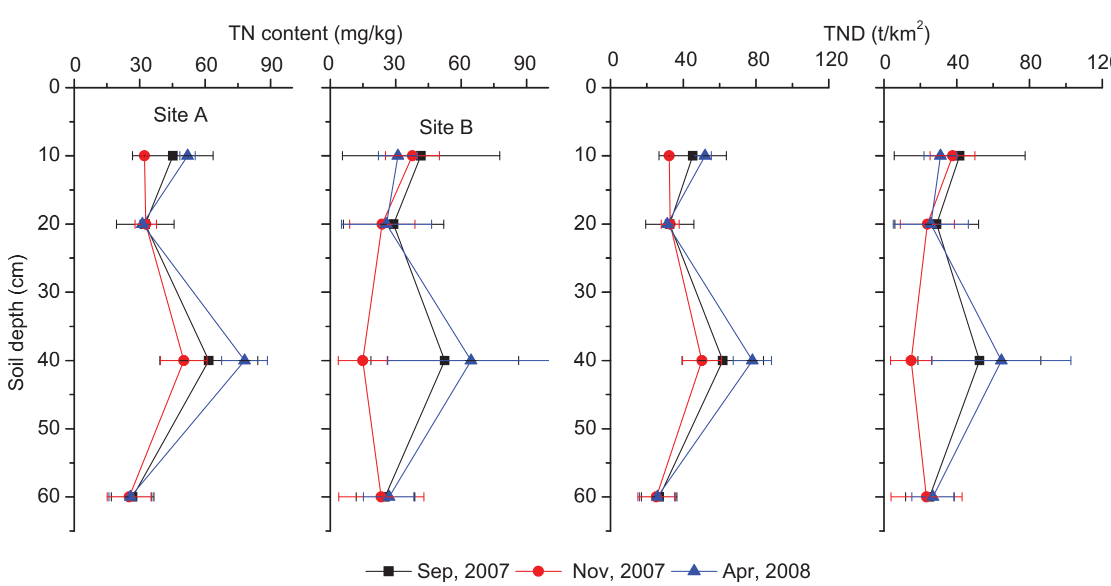

Figure 4. Profile distributions of TN and TND in the tidal flooding wetland (Site A) and short-term flooding wetland (Site B) of the Yellow River Delta in three sampling dates.

TNDs was similar to that of TN contents. TN contents and densities at all soil layers (except for the top 10 cm soils in November) were higher in the tidal flooding wetland (Site A) than those in the short-term flooding wetland (Site B) in three sampling dates. This was associated with different soil hydrological conditions because slow decomposition rates of SOM under flooded environment [2, 12]. Correlation analysis showed that TN contents were significantly correlated with soil moisture at Site A (Tab. 1). Therefore, different soil hydrological conditions in two marshes with different flooding frequencies would affect the changes in TN contents and densities. Additionally, TN contents were significantly correlated with Bd, soil depth and pH at Site A (Tab. 1), whereas there was significant correlations between TN and AP, SOC, and NO_3^-–N at Site B.

3.2.2 Spatial and temporal distribution pattern of TN contents and densities

Figure 5 shows spatial distribution of TN contents and densities along the sampling zones in different sampling dates. A graded tone scheme legend to the contents was used to show TN and TND levels. TN contents generally showed similar distribution (i.e., gradually decreased with depth) along the sampling zone at the distance from 50 to 350 m at Site A in September. However, different distribution patterns and higher spatial variabilities were observed at Site A in November and April. The patches with lower TN contents appeared at the distance of 100 m away from the tidal creek in cold seasons, whereas we observed some patches with lower TN level in upper soils in November and some patches with higher TN level in deeper soils in April at the distance of 350 m of each sampling zone, respectively. At Site B, TN contents showed similar distribution patterns in both September and November. The patches with lower TN levels appeared at the distances of 100 and 300 m away from the Yellow River channel, respectively. Moreover, TN was accumulated in bottom soils at the distance from 300 to 350 m However, in April, one patch with higher TN level and another patch with lower TN level appeared in middle soils (20–40 cm) at the distances of 100 and 300 m away from the Yellow River channel, respectively. The leaching of dissolved organic nitrogen and nitrate nitrogen could move nitrogen downward [10, 29]. Similar to SOC distribution, spatial variability of landform and soil hydrology in sampling zones at a small scale could be the potential explanation for different distribution patterns of TN [11], because the denitrified

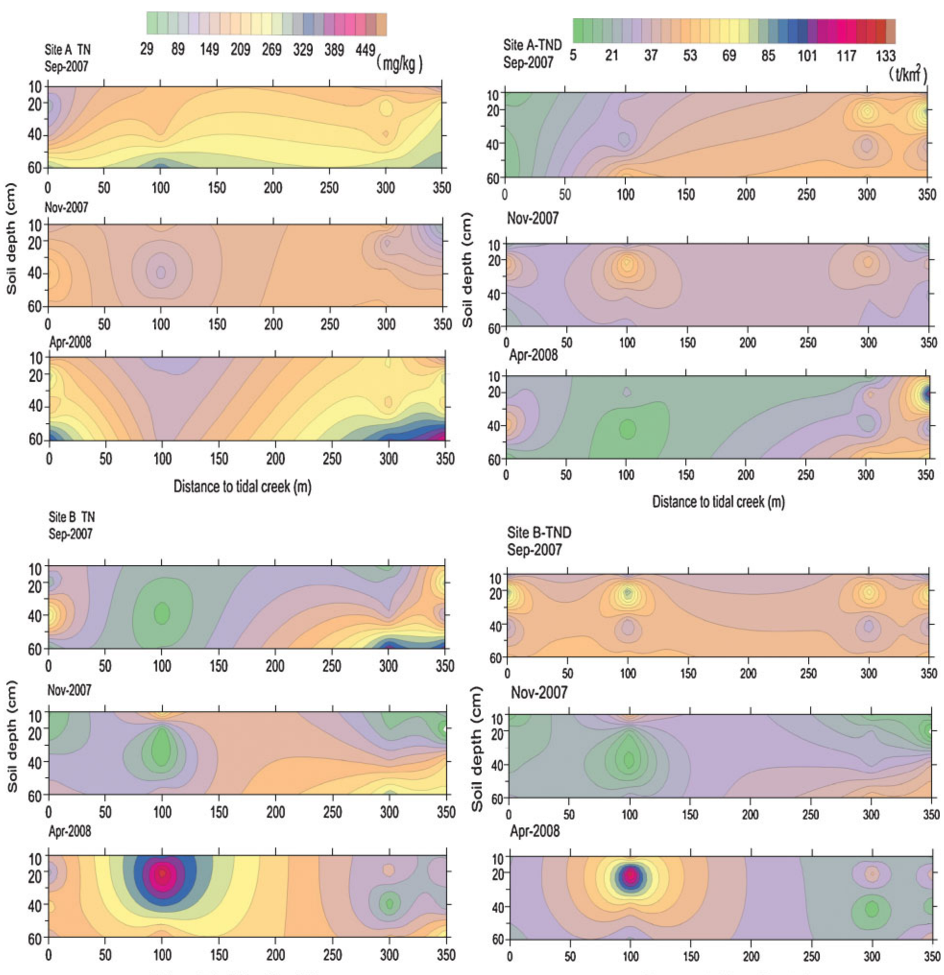

Figure 5. Spatial and temporal distributions of TN and TND in the tidal flooding wetland (Site A) and short-term flooding wetland (Site B) of the Yellow River Delta in three sampling dates.

nitrogen was directly proportional to the log mean water residence time [30].

TN contents along the sampling zones were generally higher at Site A than those at Site B. This was likely related to the inputs of tidal water at Site A, since sea water could bring the external nitrogen to tidal wetlands [31]. Moreover, Liu et al. [21] reported that seasonal-flooded or short-term-flooded plants had higher decomposition rates, whereas tidal-flooded plants had higher nitrogen return rate. Additionally, Deumlich [32] found that nitrogen loss was greater in previously dry soils whereas it was small in continuously flooded soils, because prolong drying could increase the release of mineral nitrogen.

As shown in Fig. 5, TND showed different distribution patterns from TN content at Site A. TND increased with the increasing distances along the sampling zone in September. TND showed homogeneous distribution pattern in November except for three patches with higher TND at the distances of 0, 100, and 300 m away from the tidal creek, which was opposite to that of TN content. In April, a large patch with lower TND appeared at the distance of 100 m of this sampling zone, whereas two small patches with higher TND at the distances of 0 and 350 m. This implied that soil Bd was the dominant factor influencing TND. However, at Site B, spatial distribution patterns of TND in November and April were consistent with those of TN content, which indicating TNDs were dominantly controlled by TN contents. Additionally, homogeneous distribution pattern along the sampling zone except for some patches with higher or lower TNDs were observed at Site B in September. Therefore, the contributions of TN contents and Bd to TNDs were influenced by sampling dates and sites.

3.3 Spatial and temporal variations in carbon/nitrogen (C/N) ratio in marsh soils of two wetlands

The C/N ratio of soil is a sensitive indicator of soil quality and it is also widely used to reflect the balance of carbon and nitrogen of soils. Figure 6 illustrates the variations of soil C/N ratios along the sampling zones of two marsh wetlands. The obvious differences of C/N ratios were observed between both sites in each sampling date. The C/N ratios ranged from 23 to 43 along the sampling zone from 0 to 50 m at Site A in September, whereas they were consistently lower (<23) along the zone from 50 to 350 m. Oppositely, higher C/N ratios (23–63) appeared at the distance of 350 m in November, and lower C/N ratios (13–23) were observed along the sampling zone from 0 to 300 m. Similarly, the C/N ratios (<23) were consistently lower in the whole sampling zone in April. Compared to Site A, higher C/N ratios were observed at Site B in three sampling dates except for a big patch with lower C/N ratio (<13) in November. This indicated more nitrogen could be accumulated at Site A compared to Site B since lower C/N ratios contribute to nitrogen accumulation [10]. Variations in C/N ratios were greatly influenced by SOC and TN contents and their transformation processes [2, 11]. In this study, we observed significant correlations between C/N ratios, TN and soil moisture at Site A ($p < 0.05$, Tab. 1). This might be ascribed to the strong denitrification in tidal flooding wetland. Additionally, Goodale and Aber [33] reported that C/N ratio was negatively correlated with nitrification rate ($p < 0.05$) in hardwood soils. The C/N ratio was significantly correlated with Bd ($p < 0.05$) and TN ($p < 0.01$) at both sites (Tabs. 1 and 2). This was because SOM contents were influenced by soil Bds [11].

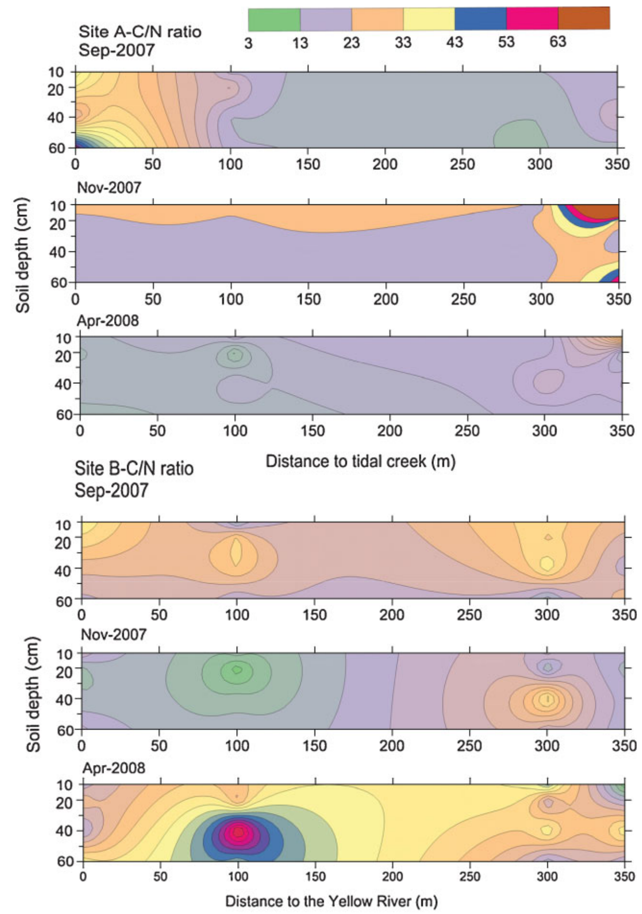

Figure 6. Spatial distributions of C/N ratios in the tidal flooding wetland (Site A) and short-term flooding wetland (Site B) of the Yellow River Delta in three sampling dates.

4 Concluding remarks

We studied spatial and temporal distribution patterns of C and N content and storage in two marsh wetlands with different flooding frequencies in the Yellow River Delta. Higher spatial variabilities of SOC and TN were observed in certain sampling date. SOC and TN contents were higher in tidal flooding wetland than those in short-term flooding wetland; whereas C/N ratios were higher in the short-term flooding wetland. SOCD and TND might be controlled by SOC and TN contents or Bds, which were closely linked to sampling sites and dates. Moreover, SOC, TN, and C/N ratios were greatly influenced by different environment factors, of which soil hydrology controlled by flooding frequencies might be the most important influencing factor in coastal wetlands. However, further studies concerning the influencing mechanisms of soil hydrology on SOC and TN content and storage are still needed. It is also necessary to consider spatial variability and sampling dates to accurately estimate carbon and nitrogen stocks in wetland ecosystems.

Acknowledgments

This work was financially supported by the National Basic Research Program (no. 2010CB951102), the National Natural Science Found (no. 51179006), the Program for New Century Excellent Talents in University (NECT-10-0235), and the Project supported by the Fok

Ying-Tong Education Foundation for Young Teachers in the Higher Education Institutions of China (no. 132009). The authors acknowledge all colleagues for their contribution in the field works.

The authors have declared no conflict of interest.

References

[1] L. B. Huang, J. H. Bai, B. Chen, K. J. Zhang, C. Huang, P. P. Liu, Two-decade Wetland Cultivation and Its Effects on Soil Properties in Salt Marshes in the Yellow River Delta, China, *Ecol. Info.* **2012**, *10*, 49–55.

[2] K. R. Reddy, R. D. DeLaune, *Biogeochemistry of Wetlands: Science and Applications*, 1st Ed., CRC Press, Boca Raton, FL **2008**.

[3] B. Zhong, Y. J. Xu, Risk of Inundation to Coastal Wetlands and Soil Organic Carbon and Organic Nitrogen Accounting in Louisiana, USA, *Environ. Sci. Technol.* **2011**, *45*, 8241–8246.

[4] W. J. Mitsch, J. G. Gosselink, *BT Wetlands*, 3rd Ed., John Wiley and Sons, New York **2000**.

[5] J. Zhang, Effects of Global Climate Change on C and N Circulation in Natural Soils, *Chin. Geogr. Sci.* **1998**, *18 (5)*, 463–471 (in Chinese).

[6] Q. Zhao, *Chinese Marsh Record*, Science Press, Beijing **1999**, pp. 255–260 (in Chinese).

[7] J. H. Bai, B. S. Cui, B. Chen, K. J. Zhang, W. Deng, H. F. Gao, R. Xiao, Spatial Distribution and Ecological Risk Assessment of Heavy Metals in Surface Sediments from a Typical Plateau Lake Wetland, China, *Ecol. Model.* **2011**, *222*, 301–306.

[8] W. J. Mitsch, J. G. Gosselink, *Wetlands*, 4th Ed., Wiley, New York **2007**.

[9] J. H. Bai, H. Ouyang, W. Deng, Y. M. Zhu, X. L. Zhang, Q. G. Wang, Spatial Distribution Characteristics of Organic Matter and Total Nitrogen of Marsh Soils in River Marginal Wetlands, *Geoderma* **2005**, *124*, 181–192.

[10] J. H. Bai, W. Deng, Q. G. Wang, B. S. Cui, Q. Y. Ding, Spatial Distribution of Inorganic Nitrogen Contents of Marsh Soils in a River Floodplain with Different Flood Frequencies from Soil-Defrozen Period, *Environ. Monit. Assess.* **2007**, *134*, 421–428.

[11] F. M. R. Hughes, The Influence of Flooding Regimes on Forest Distribution and Composition in the Tana River Flooding, Kenya, *J. Appl. Ecol.* **1990**, *27*, 475–491.

[12] J. Bradley, F. Cook, H. Richard, Effects of Hydrologic Connectivity on Water Chemistry, Soils, and Vegetations Structure and Function in an Intermontane Depressional Wetland Landscape, *Wetlands* **2007**, *27 (3)*, 719–738.

[13] A. Aviles, F. X. Niell, Pattern of Phosphorus Forms in a Mediterranean Shallow Estuary: Effects of Flooding Events, *Estuarine Coastal Shelf Sci.* **2005**, *64*, 786–794.

[14] A. Bourne, N. Armstrong, G. Jones, *A Preliminary Estimate of Total Nitrogen and Total Phosphorus Loading to Streams in Manitoba, Canada, Manitoba Conservation Report No. 2002-04*, Water Quality Management Section, Government of Manitoba, Winnipeg, Canada **2002**.

[15] Q. M. Hu, S. Q. Yang, W. Li, B. S. Cui, Niches of Wetland Plant Species the Yellow River Delta under Soil Nutrient Gradients, *J. Beijing Normal Univ. Natl. Sci.* **2009**, *45 (1)*, 75–79.

[16] S. R. Olsen, C. V. Cole, F. S. Watanabe, L. A. Dean, *Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate*, USDA, Washington, DC **1954**, p. 939.

[17] D. W. Nelson, L. E. Sommers, Total carbon, organic carbon and organic matter, in *Methods of Soil Analysis, Part 2, Agronomy* (Ed.: A. L. Page), American Society of Agronomy, Madison, WI **1982**, Chapter 9, pp. 539–579.

[18] A. J. Franzluebbers, J. A. Stuedemann, Bermuda Grass Management in the Southern Piedmont USA, VII. Soil-profile Organic Carbon and Total Nitrogen, *Soil Sci. Soc. Am. J.* **2005**, *69*, 1455–1462.

[19] R. Hiederer, *Distribution of Organic Carbon in Soil Profile Data*, EUR 23980 EN, European Communities, Luxembourg **2009**.

[20] E. G. Jobbágy, R. B. Jackson, The Distribution of Soil Nutrients with Depth: Global Patterns and the Imprint of Plants, *Biogeochemistry* **2011**, *53*, 51–77.

[21] P. P. Liu, Q. G. Wang, J. H. Bai, H. F. Gao, L. B. Huang, R. Xiao, Decomposition and Return of C and N of Plant Litters of *Phragmites australis* and *Suaeda salsa* in Typical Wetlands of the Yellow River Delta, China, *Procedia Environ. Sci.* **2010**, *2*, 1717–1726.

[22] L. L. Wang, C. C. Song, R. J. Ge, Y. Y. Song, D. Y. Liu, Soil Organic Carbon Storage under Different Land-use Types in Sanjian Plain, *China Environ. Sci.* **2009**, *29 (6)*, 656–660 (in Chinese).

[23] F. J. Arriaga, B. Lowery, Spatial Distribution of Carbon over an Eroded Landscape in Southwest Wisconsin, *Soil Tillage Res.* **2005**, *81*, 155–162.

[24] B. Lowery, J. Swan, T. Schumacher, A. Jones, Physical Properties of Selected Soils by Erosion Class, *J. Soil Water Conserv.* **1995**, *50*, 306–311.

[25] H. T. Wu, Sanjiang Plan. Wetland Herbaceous Litter Decomposition Factor, *J. Ecol.* **2006**, *25 (11)*, 1405–1411.

[26] J. H. Bai, H. Ouyang, R. Xiao, J. Q. Gao, H. F. Gao, B. S. Cui, Spatial Variability of Soil Carbon, Nitrogen, and Phosphorous Content and Storage in an Alpine Wetland in the Qinghai–Tibet Plateau, China, *Aust. J. Soil Res.* **2010**, *48 (8)*, 730–736.

[27] R. Hill, M. Cardaci, Denitrification and Organic Carbon Availability in Riparian Wetland Soils and Subsurface Sediments, *Soil Sci. Soc. Am. J.* **2004**, *68*, 320–325.

[28] K. R. Reddy, R. D. DeLaune, *Biogeochemistry of Wetlands: Science and Applications*, CRC Press, Boca Raton, FL **2008**.

[29] J. H. Bai, Q. G. Wang, W. Deng, H. F. Gao, W. D. Tao, R. Xiao, Spatial and Seasonal Distribution of Nitrogen in Marsh Soils of a Typical Floodplain Wetland in Northeast China, *Environ. Monit. Assess.* **2012**, *184 (3)*, 1253–1263.

[30] S. W. Nixoni, J. W. Ammerman, L. P. Atkinson, V. M. Berounsky, G. Billen, W. C. Boicourt, W. R. Boynton, et al., The Fate of Nitrogen and Phosphorus at the Land-sea margin of the North Atlantic Ocean, *Biogeochemistry* **1996**, *35*, 141–180.

[31] E. Vahtera, J. D. Conley, B. G. Gustafsson, H. Kuosa, H. Pitkänen, O. P. Savchuk, T. Tamminen, et al., Internal Ecosystem Feedbacks Enhance Nitrogen-fixing Cyanobacteria Blooms and Complicate Management in the Baltic Sea, *Am. J. Hum. Environ.* **2007**, *36 (2)*, 186–194.

[32] D. Deumlich, W. Mioduszewski, Analysis of Sediment and Nutrient Loads Due to Soil Erosion in Rivers in the Odra Catchment, in *Proceedings of the Symposium "Agricultural Effects on Ground and Surface Waters"*, Vol. 273, Wageningen **2002**, pp. 279–286.

[33] C. L. Goodale, J. D. Aber, The Long-term Effects of Land-use History on Nitrogen Cycling in Northern Hardwood Forests, *Ecol. Appl.* **2001**, *11*, 253–267.