Effects of Drainage on Dissolved Organic Carbon and Available Nitrogen and Phosphorus in Forested Wetlands of the Lesser Khingan Mountains (Postprint)

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Date: 2017-03-22T00:00:00+00:00

Abstract

We selected Larix gmelinii plantation wetlands with different drainage durations (drained in 1974, 1985, 1992, and 2003) and natural forest swamp wetlands (Larix gmelinii swamp wetlands) as study objects to investigate the effects of drainage on soil dissolved organic carbon (DOC) and available nitrogen and phosphorus in forest swamp wetlands of the Lesser Khingan Mountains. The results showed that after natural swamp drainage, soil dissolved organic carbon content in both forest wetlands with different drainage durations and natural swamp wetlands exhibited a decreasing trend along the soil vertical profile. Compared with natural forest swamp wetlands, DOC content in all soil layers of drained wetlands was significantly lower than that in natural swamp wetlands ($P < 0.05$). In natural forest swamp wetlands, the surface layer (0-10 cm) soil SOC content, DOC/SOC ratio, and soil available nitrogen content were all greater than those in drained forest swamps, but the available phosphorus content was lower than that in drained forest swamps ($P < 0.05$). In the soil surface layer (0-10 cm), drainage duration showed a significant negative correlation with DOC, SOC, DOC/SOC ratio, and soil available nitrogen, and a significant positive correlation with available phosphorus ($P < 0.05$). After natural swamp drainage, DOC content in the surface layer (0-10 cm) soil was positively correlated with available nitrogen (ammonium nitrogen, nitrate nitrogen) content and negatively correlated with available phosphorus content ($P < 0.05$).

Full Text

Preamble

ACTA ECOLOGICA SINICA
ChinaXiv Partner Journal

Vol. 37, No. 5, March 2017
DOI: 10.5846/stxb201509241960

Effect of Drainage on Dissolved Organic Carbon and Available Nitrogen and Phosphorus in the Wetland Forests of Xiaoxing' an Mountain

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Abstract: This study investigated the effects of drainage on soil dissolved organic carbon (DOC) and available nitrogen and phosphorus in forest swamp wetlands of the Xiaoxing' an Mountains by selecting *Larix gmelinii* plantation wetlands drained in different years (1974, 1985, 1992, and 2003) and a natural forest swamp wetland as research sites. The results showed that soil DOC content decreased vertically with soil depth across all sites. Compared with the natural forest wetland, DOC content in all soil layers of drained wetlands was significantly lower ($P < 0.05$). In the surface layer (0–10 cm), soil organic carbon (SOC) content, DOC/SOC ratio, and soil available nitrogen in the natural forest swamp were all higher than those in drained forests ($P < 0.05$). In contrast, available phosphorus content was lower in the natural wetland than in drained forests ($P < 0.05$). In the soil surface (0–10 cm), drainage time was significantly negatively correlated with DOC, DOC/SOC, SOC, and soil nitrogen, and significantly positively correlated with available phosphorus ($P < 0.05$). After drainage of the soil surface (0–10 cm), DOC and available nitrogen (ammonium nitrogen, nitrate nitrogen) were inversely proportional to effective phosphorus ($P < 0.05$). In forest wetlands where drainage ditches were dug, the soil moisture status was changed to promote forest growth. Overall, the Xiaoxing' an Mountain forest wetlands cover 106.96 thousand hectares with great carbon sequestration potential. Their average carbon density was higher than natural forest carbon densities in Heilongjiang Province as well as national forest vegetation carbon density levels. The wetlands therefore play an important role in regional carbon cycling. Since the 1970s, wetlands in the Xiaoxing' an Mountain forests have been greatly influenced by human activities, mainly through wetland drainage. Soil DOC movement with wetland drainage occurred in the directions of water movement, with a portion of soil DOC moving along the horizontal and vertical directions of drainage ditches or being lost directly to water bodies. Currently, research on human activity impacts on DOC mainly focuses on how wetland reclamation for farmland changes DOC, as well as the effects of different land use patterns on soil DOC. This study examined forest swamps of the Xiaoxing' an Mountain forests and conducted a quantitative analysis of changes in soil DOC and SOC after drainage and transformation to understand the role of DOC in the regional ecosystem's carbon cycle and carbon transformation mechanisms, providing a theoretical basis for management and sustainable development of regional wetland ecosystems.

Keywords: drainage; Xiaoxing' an Mountains; dissolved organic carbon; effec-

tive nitrogen and phosphorus

Funding: National Natural Science Foundation Projects (41301082, 4157012165); Heilongjiang Postdoctoral Funding Project (LRB13-200)

Received: 2015-09-24; **Online Publication Date:** 2016-07-13

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1. Study Area Overview

The study site is located at Yongqing Forest Farm, Youhao Forestry Bureau, Yichun City, northeastern Heilongjiang Province (48°03 53 N, 128°30 36 E), in the middle section of the Xiaoxing' an Mountains. The region has a temperate continental humid monsoon climate with an average annual temperature of approximately 0.4°C and average annual precipitation of 630 mm. There are two precipitation peaks: winter snowfall and July–August rainfall, with the peak period accounting for 65% of annual rainfall. The frost-free period is about 110 days. The zonal soil is dark brown forest soil, followed by meadow soil and swamp soil. The typical vegetation is Korean pine broad-leaved forest, with a forest coverage rate of 74.8%. The study area contains various wetland types including forest swamps, moss swamps, and sphagnum swamps, covering 4,302 hm^2, with *Larix gmelinii* forest swamps as the main type. Most of these have now degraded into secondary forests and plantations.

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2. Sample Collection

Sampling sites were selected in *Larix gmelinii* plantations drained in 1974, 1985, 1992, and 2003 at Yongqing Forest Farm, Youhao Forestry Bureau, Yichun City. Natural forest swamps adjacent to the drained plantations and corresponding to the swamp types used for drainage-based afforestation were selected as natural controls. The drained sites were designated PS74, PS85, PS92, and PS03. Within each plot, after removing the litter layer, soil samples were collected at depths of 0–10 cm, 10–20 cm, and 20–40 cm using a soil auger with an inner diameter of 5 cm. Fresh soil samples were brought to the laboratory, where plant and animal residues and stones were removed. One portion was immediately passed through a 2 mm sieve for measurement of soil organic carbon (SOC) and other physicochemical properties, while another portion was naturally air-dried and passed through a 0.45 m nylon sieve. Samples were stored in a refrigerator at 4°C away from light. The soil profile sampling depth was 40 cm, with three soil samples collected per layer.

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3. Experimental Methods

Soil organic carbon was determined using the high-temperature combustion method with a Multi N/C 2100 TOC analyzer. For DOC extraction, fresh soil was placed in a triangular flask with 50 mL distilled water at a 5:1 water-soil ratio, shaken for 10 minutes, and filtered. The organic carbon concentration in the extract was measured using a TOC-VCPH analyzer and converted to soil DOC content (mg/L). Soil ammonium nitrogen and nitrate nitrogen were determined using colorimetric methods. Soil available phosphorus was measured using the HClO -H SO molybdenum-antimony-scandium colorimetric method.

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4. Statistical Analysis Methods

Data were statistically analyzed using Excel 2003 and SPSS 19.0 software. One-way ANOVA was performed using SPSS 19.0, and the least significant difference (LSD) method was used for significance testing of differences between data groups. Pearson correlation analysis was conducted with significance level set at = 0.05. Data in figures and tables are presented as means, with charts produced in OriginPro 8.5.

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5. Results and Analysis

5.1 Effects of Drainage on Soil Dissolved Organic Carbon in Forest Swamp Wetlands

In the vertical profile, DOC content in wetlands of different drainage ages all showed a decreasing trend from top to bottom. In the surface layer (0–10 cm), DOC contents for PS74, PS85, PS92, and PS03 were 241.02, 307.1, 462.03, and 771.95 mg/kg, respectively, with the relationship PS74 < PS85 < PS92 < PS03 and significant differences between drainage ages ($P < 0.05$). At other soil depths, differences between drainage ages were not significant. Drainage time was significantly negatively correlated with DOC content in the surface layer (0–10 cm) ($P < 0.05$), though correlations were not significant at other depths ($P > 0.05$).

Both natural and drained forest swamps showed decreasing DOC content vertically through the profile. Compared with natural swamps, DOC content in drained forest swamps was lower at all depths: reductions of 78%, 72%, 56%, and 59% in the 0–10 cm layer; 76%, 77%, 57%, and 65% in the 10–20 cm layer; and 79%, 73%, 59%, and 32% in the 20–40 cm layer for PS74, PS85, PS92, and PS03, respectively. The reduction percentages were significantly different between drainage ages ($P < 0.05$) and showed a significant positive correlation with drainage time in the surface layer ($P < 0.05$), though correlations were not significant at other depths ($P > 0.05$).

[Figure 1: see original paper] Distribution of DOC content in the vertical section of drainage and natural forest swamp

5.2 Effects of Drainage on Soil Organic Carbon in Forest Swamp Wetlands

5.2.1 Comparison of SOC Between Natural and Drained Forest Swamps SOC contents in natural and drained forest swamps in the surface layer (0-10 cm) were 312.94, 260.68, 286.67, 225.09, and 243.77 g/kg, with the relationship PS74 < PS85 < PS92 < PS03 < XA (natural swamp) and significant differences ($P < 0.05$). Compared with natural swamps, SOC content in PS74, PS85, PS92, and PS03 decreased by 28%, 22%, 17%, and 8%, respectively. Drainage time was significantly negatively correlated with SOC content in the surface layer ($P < 0.05$), though correlations were not significant at other depths ($P > 0.05$).

5.2.2 Effects of Drainage on DOC/SOC Ratio in Forest Swamp Wetlands The DOC/SOC ratio, which reflects soil carbon pool quality and can indicate organic carbon stability, was significantly different between drained forest swamps in the 0-10 cm layer, ranging from 0.11% to 0.27% ($P < 0.05$). Drainage time was significantly negatively correlated with DOC/SOC in the surface layer ($P < 0.05$), though relationships were not significant at 10-20 cm (0.1%-0.16%, $P > 0.05$) or 20-40 cm (0.07%-0.14%, $P > 0.05$). Natural forest swamp DOC/SOC ratios were greater than those of drained forest swamps at all soil depths ($P < 0.05$).

[Figure 2: see original paper] Comparison of vertical distribution of SOC content in drainage and natural forest swamp
[Figure 3: see original paper] DOC/SOC vertical distribution characteristics of drainage forest and natural forest swamp

5.3 Effects of Drainage on Available Nitrogen in Forest Swamp Wetlands

5.3.1 Effects on Soil Available Nitrogen Available nitrogen in soil exists mainly as ammonium and nitrate forms, which are the primary nitrogen forms absorbed by plants. Ammonium nitrogen content showed no significant vertical distribution differences ($P > 0.05$). In the 0-10 cm layer, ammonium nitrogen content in drained forest swamps was significantly lower than in natural forest swamps ($P < 0.05$), gradually decreasing with drainage age and showing an extremely significant negative correlation with drainage time ($P < 0.01$). Natural swamp ammonium nitrogen content was not significantly greater than in drained forest swamps at other depths ($P > 0.05$). Drainage time was significantly positively correlated with the reduction percentage of ammonium nitrogen ($P < 0.05$).

Natural forest swamp nitrate nitrogen content was greater than in drained forest swamps at all depths, decreasing vertically from top to bottom. In the surface layer (0–10 cm), nitrate nitrogen content gradually decreased with drainage age, showing a significant negative correlation with drainage time ($P < 0.05$). Correlations were not significant at other depths ($P > 0.05$). Soil nitrate nitrogen content was positively proportional to DOC content, showing a significant positive correlation ($P < 0.05$).

[Figure 4: see original paper] Comparison chart of soil ammonium nitrogen content in drainage forest and natural forest swamp
[Figure 5: see original paper] Comparison chart of soil nitrate nitrogen content in drainage forest and natural forest swamp

5.4 Effects of Drainage on Available Phosphorus in Forest Swamp Wetlands

Soil available phosphorus content showed a decreasing trend vertically through the profile. Natural forest swamp available phosphorus content was significantly lower than in drained forest swamps ($P < 0.05$), with all layers being lower than drained soils. In the surface layer (0–10 cm), available phosphorus content increased with drainage age, showing an extremely significant positive correlation with drainage time ($P < 0.01$). Differences between drainage ages were not significant at other depths ($P > 0.05$). Soil DOC content in drained forest swamps was significantly negatively correlated with soil available phosphorus content ($P < 0.05$).

[Figure 6: see original paper] Comparison chart of soil available P content in drained forest and natural forest swamp

Table of correlation of all data

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6. Discussion

6.1 Effects on Soil Dissolved Organic Carbon

Hydrological conditions are important ecological attributes of wetlands. Changes in moisture conditions, such as soil water content and water level fluctuations, affect the direction and intensity of carbon biogeochemical processes between wetlands and the atmosphere. Drainage ditches artificially alter the moisture conditions of forest swamp wetlands, changing the water regime. After drainage, perennial or seasonal waterlogging shifts to non-waterlogged or dry conditions, soil hydrothermal environments change, and the ecosystem transitions from anaerobic to aerobic conditions, accelerating soil organic matter decomposition rates. With wetland drainage, soil DOC undergoes spatial transport—some moves along horizontal and vertical directions of drainage ditches or is lost directly to water bodies, while another portion is lost during transport. This leads to increased carbon output from wetland ecosystems.

Drainage ditch construction also changes the original wetland structure, causing strong disturbance to soils, altering vegetation types, and changing productivity, thereby affecting carbon sink functions and DOC content. As natural forests are mostly mature or near-mature with abundant litter accumulation, while plantations are in young stages with less litter, carbon density decreases. Therefore, natural forest swamp DOC content is greater than in drained wetlands, and surface DOC content (0–10 cm) in drained wetlands is lower than in undrained natural swamps, with greater reductions occurring with longer drainage duration. Additionally, as drainage time increases, pH gradually decreases, reducing the adsorption capacity of acidic soils for DOC, leading to increased DOC loss along drainage ditches.

6.2 Effects on Soil Organic Carbon

Soil organic carbon content in wetlands is a key indicator of various soil properties. High organic carbon content indicates high organic matter content, poor aeration, and high water content. Water depth significantly affects organic carbon mineralization, which is closely related to the decomposition rate of original organic matter, external energy inputs, and root systems and exudates of growing plants, as well as natural factors like precipitation and temperature. After forest swamp wetlands are drained, soil moisture decreases, shifting from anaerobic to aerobic environments. Peat and root layers are rapidly oxidized, losing carbon accumulation capacity. With reduced surface litter input and changed soil aggregate structure, soil organic carbon content decreases. Consequently, natural forest swamp organic carbon content is greater than in drained forest swamps, and surface organic carbon content (0–10 cm) in drained wetlands decreases with drainage time.

6.3 Effects on Soil Available Nitrogen and Phosphorus

Ammonium and nitrate nitrogen are directly available nitrogen forms whose content changes significantly affect nitrogen migration and transformation in wetland soils. Dissolved organic carbon and available phosphorus are also important ecological factors that significantly influence wetland ecosystem productivity. After wetland drainage, hydrothermal conditions change and soil moisture decreases. Soil scientists have found that among environmental factors, moisture greatly affects nitrogen mineralization, with rates changing according to water content. Stanford and Epstein found that nitrogen mineralization increases with water content. Reduced soil moisture after drainage lowers nitrogen mineralization levels, decreasing conversion of organic nitrogen to ammonium and nitrate, while also reducing soil adsorption capacity for these forms. Additionally, newly planted larch absorbs large amounts of available nitrogen through root uptake for growth, ultimately reducing soil available nitrogen. Therefore, natural forest swamp available nitrogen content exceeds that of drained swamps.

Available phosphorus refers to phosphorus that is effective or usable by plants. Many studies have found that soil moisture changes alter redox conditions, directly affecting iron oxide forms and phosphorus adsorption/release processes. Changes in adsorption/release alter phosphorus availability. With increased drainage duration, soil remains in an oxidized environment, reducing phosphorus adsorption capacity and increasing available phosphorus. Similarly, Zhang Yongsong et al. found that flooding increases phosphorus adsorption—although the overall soil is reduced, Fe^{2} diffuses to oxidized surface layers and forms amorphous iron oxides that strongly adsorb phosphorus, reducing its availability. Therefore, drainage makes natural forest swamp available phosphorus lower than in drained wetlands, and available phosphorus content in the surface layer (0–10 cm) increases with drainage time.

Land use changes alter vegetation cover and soil management, affecting the redistribution of available nutrients and soil organic carbon cycling. This study shows that DOC content is closely related to soil available nitrogen and phosphorus in the surface layer (0–10 cm) after drainage, being proportional to available nitrogen and inversely proportional to available phosphorus ($P < 0.05$). This conclusion is consistent with research by Lan Jiacheng.

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7. Conclusion

This study investigated the effects of drainage on soil dissolved organic carbon (DOC) and available nitrogen and phosphorus in Xiaoxing' an Mountain forest swamp wetlands. Soil DOC content in both drained and natural wetlands showed decreasing vertical patterns. Compared with natural forest swamps, DOC content in all soil layers of drained wetlands was lower ($P < 0.05$). In the surface layer (0–10 cm), natural forest swamp SOC content, DOC/SOC ratio, and available nitrogen content were all greater than in drained forest swamps, while natural swamp available phosphorus content was lower than in drained wetlands ($P < 0.05$). Drainage time was significantly negatively correlated with surface layer DOC, SOC, DOC/SOC, and soil nitrogen, and significantly positively correlated with available phosphorus ($P < 0.05$). After drainage, surface layer DOC and available nitrogen were inversely proportional to available phosphorus ($P < 0.05$). These findings indicate that DOC, SOC, DOC/SOC, and available nitrogen and phosphorus in the surface layer (0–10 cm) are closely related after drainage and can serve as indicators of soil fertility changes.

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Note: Figure translations are in progress. See original paper for figures.