



Drained coastal peatlands: A potential nitrogen source to marine ecosystems under prolonged drought and heavy storm events—A microcosm experiment



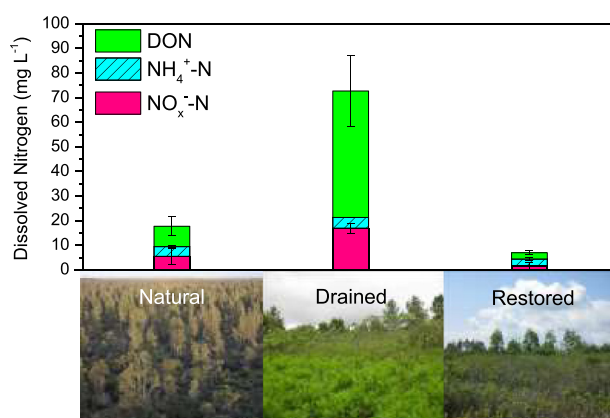
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HIGHLIGHTS

- Drought duration significantly affects the rates of nitrogen mineralization in peat.
- Rewetting following drought triggers substantial nitrogen release from peatlands.
- Drainage/drought has long-lasting effects on nitrogen transformations in peatlands.
- Drought/drainage induced plant shift raises nitrogen mineralization in peatlands.

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past several decades there has been a massive increase in coastal eutrophication, which is often caused by increased runoff input of nitrogen from landscape alterations. Peatlands, covering 3% of land area, have stored about 12–21% of global soil organic nitrogen (12–20 Pg N) around rivers, lakes and coasts over millennia and are now often drained and farmed. Their huge nitrogen pools may be released by intensified climate driven hydrologic events—prolonged droughts followed by heavy storms—and later transported to marine ecosystems. In this study, we collected peat monoliths from drained, natural, and restored coastal peatlands in the Southeastern U.S., and conducted a microcosm experiment simulating coupled prolonged-drought and storm events to (1) test whether storms could trigger a pulse of nitrogen export from drought-stressed peatlands and (2) assess how differentially hydrologic managements through shifting plant communities affect nitrogen export by combining an experiment of nitrogen release from litter.

During the drought phase, we observed a significant temporal variation in net nitrogen mineralization rate (NMR). NMR spiked in the third month and then decreased rapidly. This pattern indicates that drought duration significantly affects nitrogen mineralization in peat. NMR in the drained site reached up to $490 \pm 110 \text{ kg ha}^{-1} \text{ year}^{-1}$, about 5 times higher than in the restored site. After the 14-month drought phase, we simulated a heavy storm by bringing peat monoliths to saturation. In the discharge waters, concentrations of total dissolved nitrogen in the monoliths from the drained site ($72.7 \pm 16.3 \text{ mg L}^{-1}$) was about ten times as high as from the restored site. Our results indicate that previously drained peatlands under prolonged drought are a potent source

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of nitrogen export. Moreover, drought-induced plant community shifts to herbaceous plants substantially raise nitrogen release with lasting effects by altering litter quality in peatlands.

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1. Introduction

Massive volumes of chemical nitrogen production via the Haber-Bosch process have been applied to the landscape following the industrial revolution, causing many natural ecosystems which previously acted as nitrogen sinks to become nitrogen sources to downstream waters after saturation (Aber, 1992; Bragazza et al., 2006; Lamers et al., 2000). Overloading of nitrogen is a leading cause of impairment of coastal marine ecosystems around the world (Boesch et al., 2001; Compton et al., 2011; Diaz and Rosenberg, 2008; Paerl and Piehler, 2008). Currently, most studies focus on anthropogenic nitrogen sources, like fertilizer applied in farmlands and fossil-fuel derived atmospheric deposition (Cui et al., 2013; Liu et al., 2013; Paerl, 1997; Paerl, 2009; Robert, 2008). However, chronically accumulated organic nitrogen in natural ecosystems can potentially be quickly released and become a substantial source of nitrogen pollution, exacerbating degradation of aquatic ecosystems when environmental conditions, such as climatic warming and drought, change to favor nitrogen mineralization. Studies have shown large leaching losses of nitrogen from forests (Fang et al., 2009; Perakis and Hedin, 2002). But there is another important natural ecosystem—peatland that stores not only 1/3 of global soil carbon but also 12–21% of global soil organic nitrogen (12–20 Pg N) (Joosten, 2010; Limpens et al., 2006). Some peatlands have already lost their ability to absorb nitrogen due to an overload of nitrogen (Lamers et al., 2000; Qualls and Richardson, 2003). Moreover, most peatlands are located around rivers, lakes and coasts, where they may be a potentially significant nitrogen source to the adjacent aquatic ecosystems. To date, the internal cycle of nitrogen, which is sensitive to climate change, is still poorly understood in peatlands although its impact on adjacent downstream ecosystems may be substantial (Vassiljev and Blinova, 2012; Verhoeven et al., 1988; Wray and Bayley, 2008).

Soil nitrogen in peat is highly concentrated and is about 10–40 times higher than concentrations found in mineral soils (Soper and Osbon, 1922). Generally, nitrogen mineralization is slow under waterlogged conditions and almost all mineralized nitrogen is recycled within peatlands (Lamers et al., 2000). However, if water level drops, making more oxygen available in the soil, nitrogen mineralization could be accelerated, and huge amounts of available nitrogen can be released (Qualls and Richardson, 2003). For example, nitrogen mineralization rate found in Histosols in New York was $>500 \text{ kg N ha}^{-1} \text{ year}^{-1}$ (Guthrie and Duxbury, 1978), which is higher than the amount of chemical nitrogen fertilizer used in intensive farming (Ju et al., 2009). Such potentially high available nitrogen in soil is the main reason why large portions of peatlands were drained and reclaimed as farmlands for the past two hundred years (Richardson, 1983, 2008; Soper and Osbon, 1922). In Estonia, export of nitrogen from drained peatlands was >1.5 -fold higher than from that of farmlands and was the major source of nitrogen export to the surface water (Vassiljev and Blinova, 2012).

Both climatic and human disturbance have been substantially lowering peatland water levels and already have driven over 11% of global peatlands into a degraded state (IPCC, 2007; Joosten, 2010). The altered hydrological conditions not only directly alter the rate of nitrogen mineralization by changing the availability of oxygen but also the composition of organic nitrogen for mineralization by gradually changing the dominant plant communities that may even have longer-lasting effects on the nitrogen cycle (Laiho et al., 2003). Importantly, drought durations are projected to increase in the future (IPCC, 2007), which could substantially increase the available nitrogen pool in peatlands. Therefore, large quantities of nitrogen in peatlands would likely be

released to freshwater bodies during heavy storms and subsequently enter coastal estuarine and marine ecosystems with negative consequences (Boesch et al., 2001; Diaz and Rosenberg, 2008; Paerl and Piehler, 2008).

In this study, we collected peat monoliths from drained, natural and restored coastal peatlands in the Southeastern U.S. and conducted a microcosm experiment. We simulated prolonged drought and heavy storms in lab to test 1) whether intensive drought and storms can cause increased export of nitrogen from drought-stressed peatlands and 2) how drought duration and long-term hydrologic conditions (drainage and restoration versus natural hydrologic regimes) affect this process. We compared these outputs with measured regional estimates of nitrogen losses from peatlands from the same area.

2. Material and methods

2.1. Study sites

Along the south Atlantic coast, peatlands cover millions of hectares and store over 20% of peat in the continental USA (Richardson, 2012; Soper and Osbon, 1922). These temperate and subtropical peatlands, called pocosins, are generally dominated by shrubs and trees. Our study area is located at Pocosin Lakes National Wildlife Refuge (PLNWR) in North Carolina and is about 8 km away from estuarine and marine wetlands. This site has a warm, humid climate with an average annual temperature of 16.8 °C. Annual precipitation is around 1230 mm and about 800 mm is lost to evapotranspiration (ET). Generally, the lowest and highest water levels occur in summer and winter, respectively. Throughout the year, groundwater levels rarely rise above ground surface and often reach 20 cm below the surface, but fall to over 100 cm in depth in the summer (Wang et al., 2015).

Most of the pocosins were drained for farming between 1920s and 1940s (McMullan Jr., 1983). Currently, there are a series of distinct hydrologic units (800 m × 1600 m cells) divided by ditches that have been used by PLNWR to restore the water level since the 1990s. In this study natural, drained, and restored sites were selected for treatments. The natural site experiences natural hydrologic conditions. The water level ranges from 0 to 60 cm below the ground surface during the winter and over 100 cm during the summer. Mature canopy trees—including pond pine (*Pinus serotina* Michx.), loblolly bay (*Gordonia lasianthus* (L.) Ellis), fetterbush lyonia (*Lyonia lucida* (Lam.) K. Koch), and swamp bay (*Persea palustris* (Raf.) Sarg.)—cover about 80% of the natural site. The water level in the drained site is mostly below 50 cm depth and over 150 cm in summer. About 80% of the ground area in the drained site is covered by western brackenfern (*Pteridium aquilinum* (L.) Kuhn). In the restored site, the water level is 20–30 cm below ground surface and native shrubs are dominant species, including large gallberry (*Ilex coriacea* (Pursh) Chapm.), inkberry (*Ilex glabra* (L.) A. Gray), fetterbush lyonia, honeycup (*Zenobia pulverulenta* (W. Bartram ex Willd.) Pollard), and laurel greenbrier (*Smilax laurifolia* L.).

2.2. Microcosm experiment

We collected triplicate peat monoliths from the natural, drained, and restored pocosins in January 2011. In the field, peat monoliths (32 cm in diameter) were excavated in 10-cm increments to a depth of 40 cm and was transferred to a top-open plastic incubator (30-cm diameter, 37.5-cm depth). All vegetation, fresh litter, live roots and rhizomes ($>1 \text{ mm}$ diameter) were removed. We incubated these monoliths at a constant temperature of 25 °C in the lab creating a gradual loss

of soil water by evaporation to simulate a prolonged drought. After a 14-month drought, we rewetted these monoliths to a saturated state to simulate a heavy-storm event (160 mm).

During the drought phase, we determined net nitrogen mineralization rate (NMR) that was calculated from the changes of total inorganic nitrogen ($\text{NH}_4^+\text{-N}$ and $\text{NO}_x^-\text{-N}$) in the monolith as a function of time and area. Soil cores (3.5-cm diameter) were collected from the monoliths on 30th, 60th, 91st, 152nd and 415th day. The core was sliced into four segments (0–5, 5–15, 15–25, and 25–38 cm). Each segment was mixed and divided into three subsamples in which one was extracted using 2 M KCl and filtered by a 0.22- μm nylon filter (Micron Separations INC, MA, USA) on the first day, one was dried by oven at 60 °C for 24 h, and the last was stored in a 4 °C cold room. Soil pH was measured with a Beckman 360 pH meter, using a soil:water ratio of 1:10. We measured soil water content for each fresh sample, and all soil properties were calculated based on dry weight. On the 4th day of rewetting, we collected the leached water from the incubators and measured pH, total inorganic nitrogen and total organic nitrogen.

2.3. Potential release of nitrogen from litter

To test whether the historic hydrological conditions have potential long-lasting effects on nitrogen release due to changing plant communities with different quality of litter, we collected senesced leaves and small branches from dominant species in the natural, drained, and restored sites in 2011 and conducted a water-extraction experiment. The leaves and branches were air dried first and then put in an oven at 60 °C for 48 h. About 5 g of dry sample was ground and passed through a 250 μm (no. 60) sieve. We put 0.25–0.30 g of sample into 15 mL deionized water, mixed them by a shaker for 48 h at 25 °C. The suspension liquid was filtered through a glass fiber filter (0.5 μm , GE Water & Process Technologies, USA) and stored at 4 °C in a refrigerator for analysis of total dissolved nitrogen (TDN) and dissolved organic carbon (DOC).

2.4. Chemical analysis

DOC in the discharged water and water extraction were both determined as the difference between total C and inorganic C by a total C analyzer (Shimadzu 5000A, Kyoto, Japan). Inorganic nitrogen (NH_4^+ and NO_x^- ($\text{NO}_3^- + \text{NO}_2^-$)) in the KCl extraction and discharged water was measured colorimetrically using a flow-injection analyzer (Lachat QuikChem 8000, Wisconsin, USA). Total dissolved nitrogen (TDN) in the discharged water and water extraction was determined by a total organic carbon analyzer with a total nitrogen measuring unit (Shimadzu TOC-L, Kyoto, Japan). Dissolved organic nitrogen (DON) was calculated based on the difference between total dissolved nitrogen and total inorganic nitrogen. Total carbon and nitrogen from the dried and milled soil samples were directly analyzed with combustion CN soil analyzer equipped with a TCD detector (ThermoQuest Flash EA1112, Milan, Italy).

2.5. Statistical analysis

We tested the parameter differences among sites by one-way ANOVA using SAS 9.3. Results were considered significant at the 95% confidence ($\alpha = 0.05$). Standard error was calculated for means and error bars.

3. Results

3.1. Effects of drought

During the 14-month drought experiment, soil moisture (SM) gradually decreased, and finally about 70 to 80% of water in soil was lost in all peat monoliths (Fig. 1a). SM was always higher in the monoliths from the restored site than those from other sites. Peat monoliths from the natural site showed higher soil pH than those from the drained and the restored sites (Fig. 1b). Along with the increasing drought stress, soil pH responded differently among peat monoliths from the

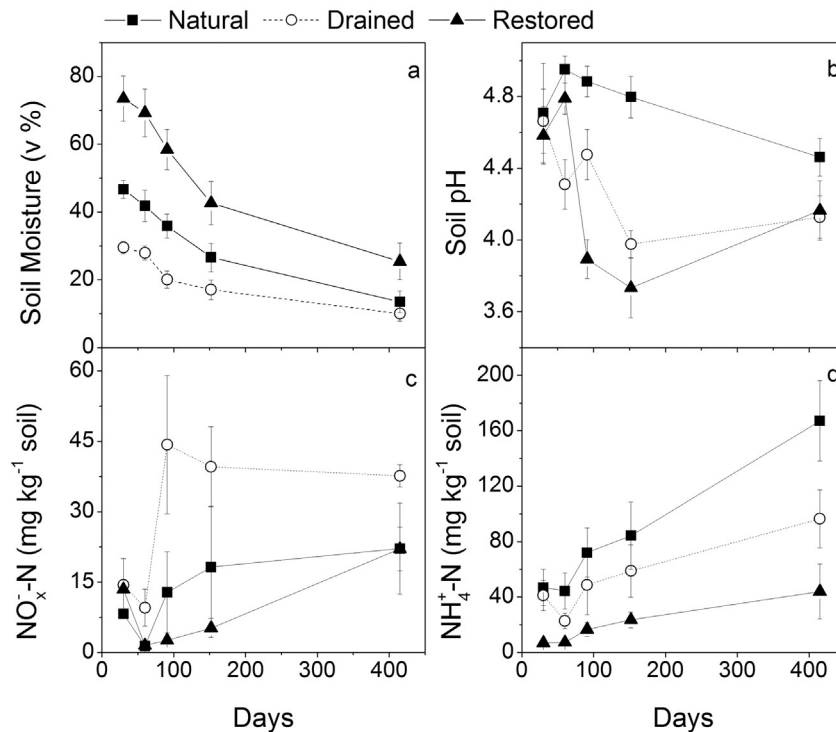


Fig. 1. Temporal variation of soil moisture (a), soil pH (b), $\text{NO}_x^-\text{-N}$ (c) and $\text{NH}_4^+\text{-N}$ (d) during the drought phase in the peat monoliths from the natural, drained, and restored sites in the pocosins of coastal North Carolina.

different sites. At the natural site, soil pH increased first and then gradually decreased. At the restored site, it increased initially, then sharply decreased during days 60–150 and slowly increased after 150 days. At the drained site, it decreased first and gradually increased afterwards. We observed the highest extractable NO_x^- -N (Fig. 1c) in the peat monoliths from the drained site and the highest extractable NH_4^+ -N from the natural site (Fig. 1d). The concentration of NH_4^+ -N was much higher than NO_x^- -N in all peat monoliths, and the ratios of NH_4^+ -N to NO_x^- -N were 11.2 ± 5.4 , 3.6 ± 1.1 and 2.1 ± 0.3 in the natural, restored, and drained sites, respectively. Peat monoliths from the restored site always contained the lowest extractable NO_x^- -N and NH_4^+ -N (Fig. 1c,d). Both extractable NO_x^- -N and NH_4^+ -N decreased in the second month of drought, then quickly increased in the third month, and later increased slowly in all peat monoliths except that NO_x^- -N did not change in the drained site after 5 months (Fig. 1c,d). Based on the temporal changes of extractable inorganic nitrogen (NO_x^- -N + NH_4^+ -N), net nitrogen mineralization rates (NMR) were calculated. We found similar temporal variations of NMR from all sites (Fig. 2). NMR was negative at the beginning, spiked in the third month, and significantly decreased afterwards. The increased inorganic nitrogen in the third month represented 23%, 27% and 77% of the total mineralized nitrogen in the monoliths from restored, natural, and drained sites during 14-month drought period. In the drained site, NMR reached $490 \pm 110 \text{ kg N ha}^{-1} \text{ year}^{-1}$ in the third month, which was about 5 times higher than that in the restored site.

3.2. Effects of rewetting

We found high concentrations of total dissolved nitrogen ($\text{DON} + \text{NO}_x^-$ -N + NH_4^+ -N) in the discharge water— 72.7 ± 16.3 , 17.7 ± 7.1 , and $7.0 \pm 1.4 \text{ mg L}^{-1}$ —in peat monoliths from the drained, natural, and restored sites, respectively (Fig. 3). Peat monoliths from the drained site also released the highest DON and NO_x^- -N, which were about 20 and 5 times as high as those from the restored site. DON represented about 68% of total dissolved nitrogen in the peat monolith from the drained site and 36% from the restored site (Fig. 3). Concentrations of NH_4^+ -N in the discharged water from all peat monoliths were similar although these peat monoliths contained different amount of NH_4^+ -N (Fig. 1d and Fig. 3). The ratio of DOC to DON was 11 times higher in the restored site (42.8 ± 7.8) than in the drained site (Fig. 4).

3.3. Potential release of nitrogen from litter

Total nitrogen (TN) in leaves of bracken fern in the drained site (about 2% of dry biomass) was two times as high as that in leaves

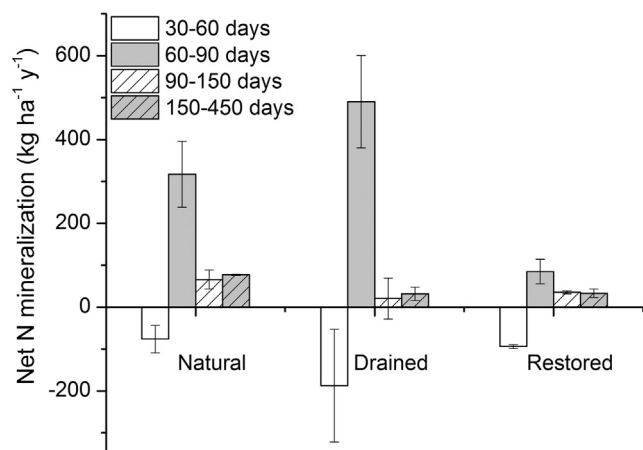


Fig. 2. Net N mineralization during the drought phase in the peat monoliths from the natural, drained, and restored sites in the pocosins of coastal North Carolina.

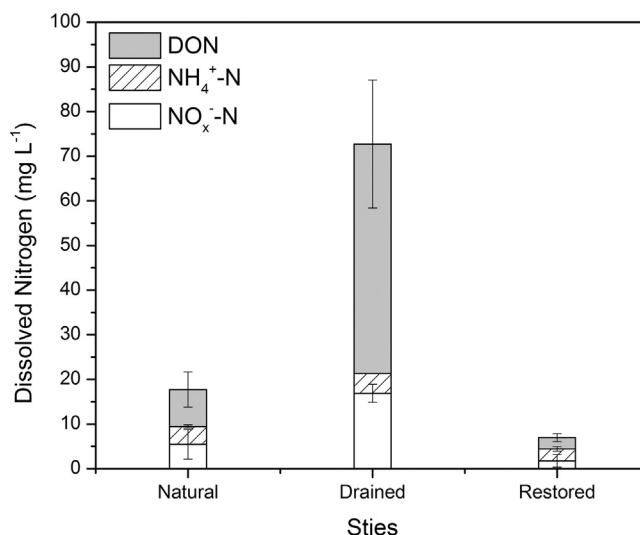


Fig. 3. The concentrations of dissolved organic nitrogen (DON), NH_4^+ -N and NO_x^- -N in the discharged water from the peat monoliths from the natural, drained, and restored sites in the pocosins of coastal North Carolina during the rewetting phase.

from shrub/tree in the natural and restored sites. Other than leaves, woody materials (branches, cones and eventually tree trunks) were major sources of litter in the natural and restored sites. All small branches we collected contained much lower TN ranging from 0.25% to 0.61%. Based on the water-extraction experiment, the leaves of bracken fern ($0.84 \pm 0.16 \text{ mg N g}^{-1} \text{ dw}$) released much higher total dissolved nitrogen compared to the leaves ($0.17 \pm 0.02 \text{ mg N g}^{-1} \text{ dw}$) and branches ($0.08 \pm 0.01 \text{ mg N g}^{-1} \text{ dw}$) from the shrubs/trees in the natural and restored sites (Fig. 5a). Consistent with the rewetting experiment, the water extraction from the leaves of bracken fern in the drained site showed a lower ratio of DOC to DON (Fig. 5b) than leaves of shrubs/trees in the natural and restored sites.

4. Discussion

All plant-free peat monoliths in this experiment were incubated under uniform temperatures. Therefore, any changes in nitrogen mineralization resulted from the simulated drought and pre-existing

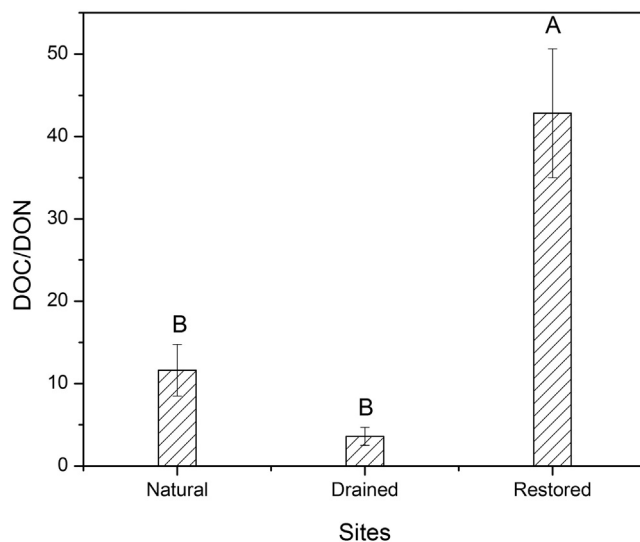


Fig. 4. The ratio of dissolved organic carbon (DOC) to dissolved organic nitrogen (DON) in the discharge water from the peat monoliths from the natural, drained and restored sites in the pocosins of coastal North Carolina. Different letters indicate a significant difference.

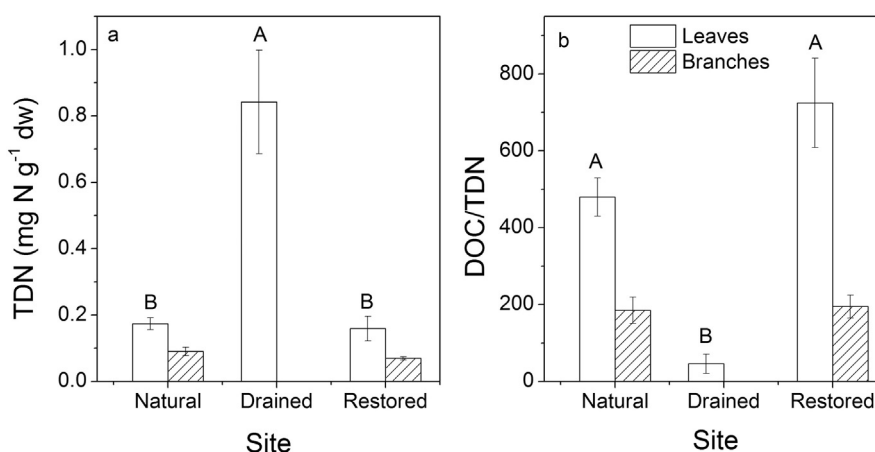


Fig. 5. TDN–Total dissolved nitrogen (a) and the ratio of dissolved organic carbon (DOC) to TDN (b) from senescent leaves and shrub branches in the natural, drained and restored sites in pocosins of coastal North Carolina. Different letters indicate a significant difference.

(>20 years) hydrological conditions. Most previously studied drought incubation experiments were relatively short-term manipulations, between several days and 1–2 months (Estop-Aragonés and Blodau, 2012; Fierer and Schimel, 2002; Venterink et al., 2002). In this experiment, we employed a 14-month drought, which is a rare but realistic event in our field situation, thus conducive to detecting an effect of long-term drought durations (Wang et al. 2015). The strong temporal variations of NMR (Fig. 2) implied that drought duration has substantial effects on the pool of available nitrogen in peatlands. At the beginning of the drought, both NO_x^- -N and NH_4^+ -N decreased (Fig. 1c,d), resulting in negative NMRs. Venterink et al. (2002) also found negative NMR during the first 12 days of drought manipulation (Venterink et al., 2002). The negative NMRs implied that the growth of microbes in our study area was still limited by nitrogen and the available inorganic nitrogen was rapidly assimilated into microbial biomass during short-term drought, and this also indicated that short-term drought may only have minor impacts on nitrogen loss in N-limited peatlands. However, NMR sharply increased during the third month (Fig. 2). Although such spikes were of short duration, the mineralized nitrogen had major contributions to the accumulated inorganic nitrogen for the 14-month drought period. Therefore, if drought lasts longer, often over 2 months in pocosin (Richardson, 2012; Richardson and McCarthy, 1994), substantial nitrogen will be quickly released. The further reduction of soil moisture possibly limited nitrogen mineralization, resulting in much lower NMR afterward this period. Similar to what other studies found (Dominik and Jörg, 2007; Frank et al., 2014; Laine et al., 2013), ammonium was the dominant inorganic nitrogen and gradually accumulated in peat during drought (Figs. 1c,d). Although the peat soils in the monoliths were under aerobic conditions, nitrification rates were low except in drained and natural sites during the third month. Low pH (Fig. 1b) in our experiment might have restricted nitrification activity (Bridgham et al., 2001), and hence the internal cycling of inorganic N in peatlands largely led to NH_4^+ -N buildups.

As expected, heavy storm simulations triggered substantial nitrogen loss from the peat monoliths after a prolonged drought. The previously drained peat released the highest nitrogen. Importantly our results are consistent with field observation in pocosins in 1999 (Shelby et al., 2005). In 1999 they experienced a very dry late winter, spring and summer followed by an unprecedented series of heavy storms (555 mm in September and October). Total nitrogen export from a forested subwatershed in the pocosins was 10 kg ha^{-1} during the storm, which is nearly as high as total loss of nitrogen for an average year. The total nitrogen concentration observed in a nearby drained forested site were abnormally high (12.3 mg L^{-1}) compared to other undrained pocosin sites (0.9 – 1.6 mg L^{-1}) (Chescheir et al., 2003; Shelby et al., 2005). We found similar results when we compared the monoliths

from the drained, natural and restored sites, the monoliths from the restored and natural sites had much lower risk of TDN loss even after a 14-month drought. Such differences between the drained and restored sites suggest that 1) long-term hydrological conditions change the internal nitrogen cycle with long-lasting impacts in peatlands and 2) drainage/long-term drought makes peatlands more fragile and sensitive to further drought than saturated peatlands. Based on the hydrology and water quality data spanning 25 years (1976–2000) in over 100 forest sites around the pocosin region (Chescheir et al., 2003), the drained organic soil sites with high hydraulic conductivities released the highest dissolved inorganic nitrogen— $10.1 \text{ kg ha}^{-1} \text{ year}^{-1}$ which was about 15–50 times higher than the unditched natural organic soil site. Compared to the natural and restored sites, higher total nitrogen in senescent leaves of herbaceous plants from the drained sites indicates that recent litter can supply more nitrogen to the drained peatlands and plant community over there can assimilate more nitrogen. Our water extraction experiment further demonstrated that herb and fern litter in a drained peatland can also release more nitrogen (Fig. 5a). Herbaceous species in drained peatlands can assimilate more inorganic nitrogen temporarily, however, their litter with low ratio of carbon to nitrogen is easy to be decomposed and releases more inorganic nitrogen not only to downstream ecosystem during storm but also to the old peat in deeper layers to stimulate the mineralization of nitrogen historically stored. Therefore, drainage/drought-induced plant community shifts to more herbaceous species change the quality of litter, which may substantially affect the nitrogen transformation processes in peatlands.

Additionally, all peat monoliths contained much more NH_4^+ -N than NO_x^- -N at the end of the drought phase experiment (Fig. 1c,d). However, in the discharge water, the concentration of NH_4^+ -N was lower than NO_x^- -N in the drained site and similar in the natural and restored sites (Fig. 3). Therefore, a large portion of NH_4^+ -N remains bound to cation exchange sites on the soil complex, which suggests storms can only flush out a small amount of NH_4^+ -N to the downstream. In line with other studies (Bragazza and Limpens, 2004; Frank et al., 2014; Qualls and Richardson, 2003), DON was the dominant form of nitrogen in the discharge water (Fig. 3). The monoliths from the drained site showed unexpectedly high DON concentration (Fig. 3), which suggest drainage not only enhances the release of nitrate but also DON. Peat in the drained site contained higher inorganic nitrogen by increased nitrogen mineralization, which possibly promote microbial dissolution of organic compounds and hence increase the production of DON like amino acids (released during the hydrolysis of proteins) (Kalbitz and Geyer, 2002; Qualls, 2000). In our study, the ratio of DOC to DON was lower in the drained and natural sites than in the restored site, which suggest a preferential release of DON (Kalbitz and Geyer, 2002) from the natural and

drained sites (Figs. 3, 4). This was consistent with our water extraction experiment in which leaves from the drained site also showed a lower ratio of DOC/TDN.

In conclusion, our findings showed that prolonged drought followed by heavy storms leads to a high risk of nitrogen export from peatlands, especially from drained/degraded peatlands, to downstream coastal waters. We also found that drainage/drought-induced plant community shifts change the litter quality with substantial effects on the internal nitrogen cycle, and thus may have long-lasting impacts on the response of nitrogen transformations to climate induced drought changes. Our results also indicate that restoring drained/degraded peatlands by raising water levels is conducive to conserving nitrogen. However, water levels in drained or degraded peatlands should be increased gradually during restoration to leave enough time for nitrogen immobilization and uptake by adapted microbe and plants in wetter conditions, otherwise, enormous amounts of nitrogen may be quickly released from drained peatlands after complete rewetting or a heavy storm.

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