Executive Summary:

Natural peatlands are threatened by projected increases in prolonged droughts, drainage and increased temperatures according to recent IPCC models. Millions of hectares of former peatlands have been drained and converted to agriculture and forestry in the U.S. However, while drought and drainage promotes the decomposition of organic matter in soil, leading to accelerated soil subsidence, and severe carbon losses in northern sphagnum peatlands, shrub dominated SE peatlands seemingly defy accelerated loss of carbon. These southern peat-based wetlands, or peatlands, cover several million acres throughout the SE region and encompass well known National Wildlife Refuges (NWR), State Game lands and areas managed for conservation by The Nature Conservancy (TNC) that range from the Great Dismal Swamp NWR (NC/VA) to the Apalachicola National Forest in FL. Spatial analysis by the TNC shows that of the nearly 1.1 million acres of peatlands, hundreds-of-thousands of acres of peatlands (which are characterized as Histosols soil) in the SE U.S. have been drained and converted into agriculture, forest, or are fallow lands due to their low productivity. Soil and drainage conditions in altered areas promote loss of millions of tons of carbon each year due to increased greenhouse gas (GHG) losses, reduced carbon sequestration and uncontrolled deep peat fires.

The USFWS and TNC have partnered with the Duke University Wetland Center to verify estimates of the C and N sequestration potential of drained versus restored peatlands at Pocosin Lakes National
Wildlife Refuge (PLNWR). Our current findings at PLNWR shows that peats are sustainable in large part due to restoration of hydrologic conditions that more closely matched natural sites, which maintains native fire adapted plant species driven production of phenolic compounds, which are found in varying amounts in the Histosols. These varying amounts of phenolic compounds can be optimized for under specific hydrologic regimes and managed to enhance C sequestration and reduce GHG losses. Thus, hydrologic management and fire management are keys to maintaining fire adapted native plant species whose phenolic production in peats may be the latchkeys that control C sequestration and GHG losses in other SE peatlands, but this is unknown.

Significant findings to-date in the field experiment show that although a higher temperature and lower summer water level exist in NC shrub peatlands at PLNWR, soil respiration is much lower compared to boreal peatlands. Comparative field studies of GHG fluxes in replicated drained, restored and reference sites indicate that losses were greatest for CO$_2$ and very low for N$_2$O and CH$_4$. CH$_4$ and N$_2$O emissions at PLNWR thus appear to have a negligible contribution to global radiative balance, although additional seasonal and data on converted agriculture lands are needed to verify if this is a long-term trend. Comparison of treatments found higher CO$_2$ releases under drained soils further suggesting that drainage does result in continued massive losses of CO$_2$ and losses of soil carbon. Drainage and resulting loss of native shrubs resulted in significant losses of historical peat via CO$_2$ emissions such that the drained site peats are oxidizing more than 5 times the C that is being fixed by the plants and thus historic peats at these sites may completely disappear within 200 years if not hydrologically restored. The natural and restored sites have a positive C storage balance oxidizing on average only 38% and 56% of the litter mass found on the forest floor, respectively. The annual CO$_2$ gas losses from the biomass rich reference (natural) site averaged 11,600 kg C ha$^{-1}$ yr$^{-1}$ compared to 7,400 and 5,600 600 kg C ha$^{-1}$ yr$^{-1}$ at the drained and restored sites, respectively. The seasonal budget estimates of CO$_2$ gas fluxes over the year show that all sites lose around 50% of their annual CO$_2$ flux losses during the summer period with lowest total respiration losses occurring during the cooler winter months as expected.

Natural and restored sites compared to the drained sites were found to contain substantial polyphenol, derived from high phenolics in leaves and high lignin in native pocosin shrub leaves and stems. Importantly, regression analysis showed that polyphenol was the main factor chemical inhibiting CO$_2$ emission in natural and restored pocosin peats. Seasonal drought enhanced the release of polyphenol in soil suggesting reduced phenol oxidase activity. However, most studies in saturated boreal peatlands show that a drop in water level introduced more oxygen and accelerated the phenol oxidase activity, decomposing more polyphenol. The differing results between our seasonally unsaturated and saturated northern peatlands suggest that phenol oxidase activity may have a peak optimal moisture level threshold. Above this threshold, anoxia is the key mechanism inhibiting phenol oxidase activity in waterlogged peat soil. Below it, reduced soil moisture limits the activity, as shown for pocosins where the lowest phenol oxidase activity occurred when soil water content was <40%. Below 40% soil moisture, oxic conditions (unsaturated soils) inhibit phenol oxidase activity suggestion low soil moisture (drought conditions) limits decomposition if sufficient polyphenol is present. Consequently, more polyphenol existing under climate induced moderate drought helps native shrub peat to resist decomposition. Our findings offer new evidence that frequently occurring summer drought or climate–induced moderate drought will not appreciably increase the loss of stored carbon in unsaturated pocosin peatlands due to the recalcitrant quality of the peat. However hydrologic restoration of the drained peatlands will be essential to prevent massive losses of the remaining stored soil carbon (stop loss) in drained sites. These findings have important ramifications concerning carbon storage and losses in peatlands under future climate change
scenarios of elevated temperatures and more frequent droughts as well as the future of fallow drained SE peatlands and their potential for restoration C credits.

**Introduction and Background**

Subtropical and tropical peatlands (STPs) occur within the boundaries latitudes of 35 degrees North and South and are differentiated from other peatlands by climate and carbon-source (Andriesse 1988, Zinck 2011). Globally, approximately 1/3 of peat stores are found in STPs formed from high-lignin woody biomass (Farmer et al. 2011). STPs along south Atlantic coast from Virginia/North Carolina (VA/NC) to Florida (FL) have persisted through changing climate and sea level over the last 4000 years, and continue to accrete peat even under climate driven conditions of drought, warmer temperatures and fire (Sharitz and Gibbons 1982). According to the responses of carbon accretion/decomposition to drought and global warming in boreal *Sphagnum sp.* peatlands (Moore and Bellamy 1974, Ingram 1983, Gignac et al. 2000, Fenner and Freeman 2011), STPs should not exist and continue to accrete and store peat. For example, woody peatlands along the south Atlantic coast experience higher annual mean temperatures, recurring annual periods of summer water table drawdown of between 60 to 100 cm (Bridgham and Richardson 1993, Richardson and McCarthy 1994) and frequent low-intensity fires that logically should not favor the accumulation and long-term storage of peat, but in fact about 20% of the peat in the continental United States is stored in these areas. Similar conditions have caused large carbon losses in boreal *Sphagnum* peatlands (Ise et al. 2008, Wickland and Neff 2008, Fenner and Freeman 2011). Yet some STP ecosystems located at the northern zonal boundary have survived past periods of climate change including a transition from boreal plant communities to the present- evergreen-shrub dominated communities in response to a warming period at the end of the Wisconsin Ice Age (Whitehead 1981, Sharitz and Gibbons 1982) and have continued to accrete carbon over the past 4000-6000 years.

Pocosins, known as southeastern shrub bogs are a major example of such a survival peatland and are characterized by a very dense growth of mostly broadleaf evergreen shrubs with scattered pond pine (Richardson 2012). The typically thick layers of peat soils (Histosols) underlying pocosins are chemical sponges over geologic time, locking-up metals, carbon, and nitrogen in vegetation in the accreting organic soil layer. Under normal saturated hydrologic conditions, decomposition in organic soils is minimized due to a lack of oxygen and low pH, allowing for accumulation of organic carbon in peatlands.

However, pocosins southeast of Lake Phelps, North Carolina were drained for now defunct farming and peat mining operations. As a result their carbon, nutrient and metal retention functions were diminished and some of these constituents were released to the atmosphere and adjacent waters. When these lands became part of Pocosin Lakes National Wildlife Refuge (PLNWR) in 1990, managers began restoring water levels. This restoration returns the lands to a more natural state and is expected to sequester tons of nutrients, including nitrogen (a known source of regional water quality problems) and carbon (a known source of global climate
problems). Importantly, restored sites will retain and prevent runoff of ions and heavy metals into adjacent estuaries. There are also important opportunities to expand restoration of drained peatlands, on-and off-refuge, because over sixty percent of these lands have been degraded or drained and converted to agriculture (Figure 1). *It is hypothesized that proper hydrologic restoration would enhance carbon and nitrogen sequestration in these peatlands.* Our research provides quantitative data on sequestration benefits of restoration (scientific verification of our hypothesis). This project also fills in gaps in wetland restoration science to facilitate restoration partnerships and sound management decisions regarding carbon and nitrogen sequestration potential under managed and unmanaged hydrologic conditions on both federal and private lands.

![Fig. 1. Drained and converted organic soils in agriculture that have potential for increased greenhouse gas losses on the NC coast (unpublished map from RAMSAR working group)](image)

**Scope of Effort and General Methods**

**Experimental Design Setup and Methods**

Funding was provided in late 2009 and with this support the project team initiated a series of meetings, which were held with personnel at the PLNWR to discuss experimental design and layout (February and March, 2010). An initial set of trails were cut by PLNWR personnel to allow access to the interior of various blocks that could be used to set up hydrologic gradients to test our hypothesis. After an initial analysis of hydrologic conditions the first set of transects was completed in early May of 2010, allowing access to sites and initiation of site instrumentation for hydrology and green house gas (GHG) measurements. Final sites were selected in late 2010 and are shown in Figure 2. Three restored sites (B-7, C-2, and D-11); a reference site and a drained site (C-14) were instrumented for automatic water level readings and
initial soil samples taken for nutrient, soil chemistry and carbon analysis. Three transects were cut at different distances into sites C-14, D-11 and the reference site to establish a range of hydrologic conditions from which to test our hypothesis. Automated outflow samplers (ISCO) were also installed to determine outflow chemistry of C, N and P species. Long-term carbon accumulation in peat is measured using sediment-erosion tables (SETs) to measure vertical accretion/subsidence in conjunction with measurements of bulk density and organic carbon (Cahoon et. al., 202). SETs were installed at three sites in the spring and summer of 2012. Measurements are made every six months thereafter. Bulk density, organic carbon content, and nitrogen have been measured by collecting intact cores. In the reference wetlands, additional peat cores have been collected for radiometric $^{210}$Pb analysis to estimate historical rates of peat accretion. Above ground biomass of trees and shrubs was measured on selected field plots at each treatment site using known allometric equations for major tree species and field scale weighing of shrubs from clipped plots. Subsamples of each shrub species were returned to the lab for a wet weight/dry weight conversion. Aerial photos of each block were then used to assess the density of vegetation by type and converted to an aerial estimate of biomass for all sites. Litter was collected at a number of random sites adjacent to our GHG plots and used to estimate litter mass. Plant, soil and litter material were returned to the Duke lab for final chemical analysis of nutrients and carbon following methods outlined in Richardson (2008).

![Site map showing management blocks and experimental treatments for the carbon sequestration study at Pocosin Lakes National Wildlife Refuge NC.](image)

Replicates sets of in-situ soil respiration measurements of CO$_2$, CH$_4$ and N$_2$O have been collected monthly at each site in 2011, and 2012 and analyzed by GC analysis (Varian 450) to assess GHG flux rates under different hydrologic treatments and seasonal temperature conditions. Soil and air temperature, water table, and soil moisture in the unsaturated zone were measured during each chamber assay. We have continued to monitor concentrations of
total C, dissolved inorganic C, and dissolved organic C, total N, NO$_3^-$, NH$_4^+$, total P and ortho-P in surface waters draining the hydrologic treatment blocks. These samples are collected on a storm-by-storm basis as well as some low and high flow periods. However, a shift in the hydrologic water management plan as well as damage to weirs in PLNWR has left some sites with little or no outflow or uncorrected flows so annual budgets have not been completed to-date.

**Study Sites**

Evergreen shrub bogs, called pocosins in this area are characterized by a dense growth of broadleaf evergreen shrubs with scattered pond pine (Richardson 2012). Starting 3 to 5 cm below surface, the peat layer (up to 3 m deep) is often black, fine-grained, and highly decomposed with ash content less than 3%. Droughts and fire are common events in these peatlands. The typical long-term fire patterns of these sites fit the criteria of a Class 2 fire regime (Heinselman 1981) with frequent, light surface fires and a 1-25 year return interval (Christensen 1988). Fire under wet or moist soil conditions is important for not only maintaining the native shrub/tree community, but also for producing substantial black carbon (mostly partly burned wood material), which also contains high amounts of aromatic and phenol compounds (Knicker 2007) thus allowing for peat accumulation. Importantly, fire is unlikely to burn peat in saturated peatlands (Turetsky et al. 2011). Thus, management of hydrology and fire intensity in natural and degraded shrub/tree peatlands will be principal to maintaining peat/litter quality (phenol/black carbon), enhancing long-term carbon accumulation and preventing downstream DOC losses to coastal waters.

The study site has a warm, humid climate with an average temperature of 16.8 °C annually (January average 6.7 °C, July average 26.2 °C). Precipitation is fairly evenly distributed all year. Annual rainfall compared to evapotranspiration (ET) shows that 65% of the annual input of 1230 mm leaves as ET (800 mm). Groundwater losses are less than 1% of rainfall. High ET results in lowest water level in summer, whereas diminishing ET results in highest water level in winter. Pocosin peats are unsaturated, and the groundwater level is rarely above the surface throughout the year, and often 20 cm below with summer values often falling to 100 cm below the surface (Richardson and McCarthy 1994).

Large portions of pocosin were ditched and drained for farming in the 1970s, but after the creation of the PLNWR in the 1990s managers began to restore water level in some areas. Drainage canals divide the managed pocosin into a series of distinct hydrologic units (800 m × 1600 m cells), which allow the managers to control the water level. In this study, three sites with different hydrologic managements—reference (natural), drained, and restored—were selected for treatment. Each hydrologic management condition had been in place for more than 20 years. The natural site was maintained in unaltered hydrologic conditions with a water level ranging from 0–20 cm below the ground surface during the winter and greater than 30 cm during parts of the summer. About 80% of the area in the natural site was covered by mature canopy trees, including pond pine (*Pinus serotina* Michx.), loblolly bay (*Gordonia lasianthus* (L.) Ellis), fetterbush
(Lyonia lucida (Lam.) K. Koch), and swamp bay (Persea palustris (Raf.) Sarg.). Due to long-term drainage in the drained site the water table is mostly below 80 cm depth and greater than 120 cm in summer. The species composition has changed because of drainage. Western brakenfern (Pteridium aquilinum (L.) Kuhn) covers 80% of the ground area and winged sumac (Rhus copallinum L.) dominates the shrub community with some wax myrtle (Morella cerifera (L.) Small) and titi (Cyrilla racemiflora L.). In the restored site, the water level is raised to 20–40 cm below ground surface. The dominant species are native shrubs, including inkberry (Ilex glabra (L.) A. Gray), large gallberry (Ilex coriacea (Pursh) Chapm.), honeycup (Zenobia pulverulenta (W.Bartram ex. Willd., Pollard), fetterbush, and laurel greenbrier (Smilax laurifolia L.) with some smaller trees of pond pine, and loblolly bay.

Results To-Date

Hydrology

The hydrologic conditions on the replicated reference, restored and drained blocks at PLNWR shown significant shifts in water depths from the winter of 2011 to the spring of 2013 (Figure 3). In the winter of 2011 the drained blocks had water table depths approximately -70 cm below the surface compared to -40 cm and -20 cm for the restored and reference blocks, respectively. By August of 2011 all sites had water table depths near -140 cm below the surface due to a near record summer drought period. Hurricane Irene in the fall of 2011 quickly restored more normal hydrologic conditions with the drained sites averaging the lowest water levels near -80 cm in depth going into the spring of 2013. The exception again was the late summer months when the drained site water table dropped to -115 cm. In contrast the restored and reference blocks closely tracked each other with water tables staying nearer the surface with depths of -40 and -60 cm for the reference and restored, respectively during first half of 2012 and then both showed a rise in the water table during the late summer and fall period, the highest ET period, followed by a further winter recovery during the main rainfall season on the coast of North Carolina. Importantly the restored and reference sites closely tracked each other in terms of hydrologic conditions while the drained site remained significantly drier. All sites followed the regional rainfall pattern. These conditions allowed us to test the effects of water table depth and soil moisture on GHG losses as well as longer-term carbon sequestration.

Greenhouse Gases

Our results to-date show that CH₄ and N₂O emissions at PLNWR have a negligible contribution to global radiative balance since values were extremely low under all treatment conditions (Figure 4). CO₂ dominated gas trends at the reference, restored and drained sites, although rates were different with the reference site showing the highest annual losses of CO₂ followed by the drained and then the restored site (Figure 5). The annual CO₂ gas losses from the biomass rich reference (natural) site averaged 11,600 kg C ha⁻¹ yr⁻¹ compared to 7,400 and 5,600 600 kg C ha⁻¹ yr⁻¹ at the drained and restored sites, respectively. The annual budget of CO₂ losses
over the growing season show that all sites lost around 50% of their CO₂ emissions during the summer period with lowest total respiration losses occurring during the cooler winter months as expected.

Fig. 3. The average water table depth on reference restored and drained blocks from 2011 to 2013 at the Pocosin Lakes National Wildlife Refuge. The average values for each treatment are based on automated water wells for three sites per treatment (Total N=9).

Fig. 4. CO₂ equivalents in restored, drained and reference areas of Pocosin peatlands in PLNWR. CO₂ equivalents = Soil respiration (CO₂) + 298× N₂O + 25× CH₄ (unpublished data).
Fig. 5. Annual CO$_2$ flux from the drained, natural (reference) and restored sited during 2011 and 2012 (Richardson et al., in preparation).

Importantly, GHG findings to-date show that although a higher temperature and lower summer water level exist in shrub peatlands in the humid-subtropical SE U.S., soil respiration is much lower compared to boreal peatlands (Bridgham & Richardson 1992; Raich 1995), especially for CH$_4$ and N$_2$O emissions, which are extremely low at PLNWR (Figure 4). CO$_2$ dominated gas trends at the reference, restored and drained sites, although rates were seasonally different.

**Annual Carbon Budgets**

To complete a carbon budget we finished field collections of plant community stand biomass, and litter fall data to estimate aboveground standing C stocks during the spring of 2011. Soil peat volume and mass were also estimated for each site via a series of soil depth probes matched to C content and bulk density. Trees dominated the reference site, with shrubs being the dominant vegetation at the restored sites and ferns and small shrubs at the drained sites. The plant biomass is the second largest C storage compartment but vast differences exist among sites. Preliminary estimates of biomass indicate that the reference site has 71.9 Mg C ha$^{-1}$ compared to 20.8 Mg/ha and 4.8 Mg C ha$^{-1}$ at the restored and drained sites, respectively (Figure 6). The reference site has 3.5 and 14 times more standing biomass than the restored and drained sites, respectively. The litter layer at the reference, restored and drained sites average 30.9, 10 and 1.6 Mg C ha$^{-1}$, respectively. The litter C layer at the reference site follows the higher biomass trends found at this site and is 3 times higher than found at the restored site and 20 times higher than the drained site. Although not fully completed as canal outflows DOC fluxes are still being determined, our preliminary carbon (C) budget for the site indicates that the vast amount of C as expected are stored in the peat soil with the drained site having only about 50% of the peat found at the restored and drained site (Figure 6). While this may in part be due to the long-term
differences in C accumulation among sites it is clear that the high annual GHG flux rate from the drained site (20% more than the restored site) results in a net loss of nearly 6 Mg C ha\(^{-1}\) yr\(^{-1}\) and suggests all the peat at this site will be lost within 200 years or less unless hydrologic restoration efforts are employed. By contrast the reference and restored sites are adding 19 and 4.4 Mg C ha\(^{-1}\) yr\(^{-1}\) to the litter compartment, but only some portion will remain as long-term peat accretion. Long-term accretion (125 years) estimates from \(^{210}\)Pb measurements suggest that only about 1.3 Mg C ha\(^{-1}\) yr\(^{-1}\) (< 10%) will be accumulated long-term as peat due to continued decomposition and natural fire effects.

Gas flux measurements indicate that the drained and reference site are losing the most CO\(_2\) and CH\(_4\) with the restored site have a much lower annual rate loss. A coarse estimate from the rate of GHG losses for the reference sites suggests that only 38% of the litter C deposition would be lost each year each year after leaf fall as compared to a 5-fold increase in gas C flux losses at the drained site as it only has the capacity to produce 1.6 Mg C ha\(^{-1}\) of litter. This means that the drained site is decomposing historical peat at an alarming rate. This would suggest that the drained site would lose almost all of its’ remaining peat in approximately 2 centuries, while the reference and restored site are a sink for C. Importantly the restored site showed the lowest GHG losses, with values being much lower than current litter production. This suggests the restored site will continue to be a major net C sink and with hydrology matching the reference site should continue to increase C sequestration at an increasing rate as vegetation biomass and litter fall continues to increase. Final numbers and complete C budgets will be based on three full years of GHG measurements and better estimates of decomposition rates from over 1,000 litterbags as well as additional SET and \(^{210}\)Pb information gathered in 2013.

Fig. 6. A Carbon budget for three hydrologic regimes at PLWNR in NC. This budget is based on two years of field measurements for some compartments. Gas flux estimates are from monthly 2011-12
measurements. Although extremely low in concentrations CH₄ fluxes were added to the total GHG flux in-order-to give a more complete total C budget.

**Greenhouse Gas Responses to Hydrologic Conditions**

Our next step was to determine if CO₂ emissions are related to water table depths in the field and our first evidence of the effects of water table on fluxes came during the summer drought of 2011, which was followed by hurricane Irene on August 27, 2011, which dropped over 23 cm (9 inches) of rain in the first day. A plot of the CO₂ emissions during the drought and after the hurricane shows a dramatic drop in the amount of CO₂ emissions leaving the treatment sites after water tables rose significantly (Fig.7). There was no significant increase in the other GHG after the hurricane effects. The restored sites almost always had the lowest rates of CO₂ emissions and matched the reference sites after the rainfall in September. The drained sites had the highest CO₂ emissions after the hurricane. The CO₂ emissions during the drought period were 3 times higher than during the wet period. Clearly the lower water tables and reduced soil moisture decreased CO₂ emissions at these sites with the drained sites showing the highest hourly fluxes. However the overall effects shown here are only for two months of measurements so to determine the full impact of water table manipulations required that we make monthly measurements for several seasons and years and determine if we could predict CO₂ emissions just from water tables or soil moisture. An assessment of CO₂ emissions during 2011 and 2012 revealed that there was only a weak water table relationship versus CO₂ emissions during the summer months and no overall relationship if the entire years water tables were included in the regression (Figure 8). Finding no relationship on an annual basis is not unexpected since soil respiration is a microbial driven process that is highly temperature related with much lower values found under cold soil temperatures. Across all sites, when we included 11 environmental variables from August 2011 to July 2012 in a stepwise regression only air temperature (T), water level (WL) and volumetric soil moisture (VSM) were selected as key variables, which explained 0.41, 0.09 and 0.45 of the variation in CO₂ flux, respectively. This indicates temperature is the most important factor controlling the temporal CO₂ emission, with a Q₁₀ of about 2.0 for our study area. However, the significant CO₂ emissions with water table relationship found under more constant temperatures in the summer suggests that other factors in conjunction with temperature and hydrology are driving the variations found in summer CO₂ emissions across these sites (Figure 8). Yet, we only found a slightly better yearly relationship between CO₂ emissions and soil moisture in the top 20 cm of the peat (Figure 9). The soil moisture measurements were made at the same time our GHG flux measurements were made.

In summary, CO₂ emissions, as the main greenhouse gas in PLWNR experimental field study are significantly controlled by temperature, water level and soil moisture. Thus, hydrological restoration is essential to maintain old carbon and increase new carbon storage directly by reducing CO₂ emission, and indirectly by avoiding catastrophic fire (Keeley 2009). However, it is clear that peat decomposition, GHG fluxes and C storage in pocosins are also related to other specific environmental drivers such as the quality of peat. To explore the importance of these
factors and determine if we could develop an indicator or index related to C storage and losses we next explored the quality of the peat across our treatment sites.

Fig. 7. The hourly rate of CO$_2$ emissions during the summer drought of 2011 followed by fall rates after hurricane Irene significantly raised the water table (see Fig. 3).

Fig. 8. The relationship between CO$_2$ emissions and water table depth during each season. All treatment sites are included in this graph. The regression shown is significant for only the summer months.
Peat Quality and GHG Fluxes

Chemical characteristics of peat soil and plants in our study sites were first assessed to determine if differences existed in biogeochemical characteristics among our test sites and plant communities, which may control peat decomposition (Table 1). In the drained site, loss on ignition (LOI, $P = 0.003, n = 12$) in soil, the C/N ratios in leaves ($P = 0.01, n = 4–10$) and stems ($P = 0.005, n = 4–9$), and total phenolics in leaves ($P = 0.002, n = 4–10$) were significantly lower than those in natural (reference) and restored sites, while pH was significantly higher ($P = 0.005, n = 3$). The natural site is more nitrogen-rich than the restored site. Leaves from shrubs, a total of 12 species, contain about 116 times higher total phenolics than *Sphagnum magellanicum* Brid. found in our study area. Most importantly, the phenolics at the drained site are significantly lower than either the restored or natural sites.

To test the interaction effects of soil moisture and drought on phenolic content in soil, phenol oxidase activity and heterotrophic carbon losses over time, we implemented a drying experiment utilizing soils from our restored, drained and natural sites. Over a 5-month incubation, soil water contents of the peat monoliths consistently differed in the order of restored > natural > drained (Wang and Richardson 2013). About 42% of soil water was gradually lost to evaporation during the experiment, and final values were $43 \pm 6$ (v %), $27 \pm 4$ (v %) and $17 \pm 3$ (v %) in restored, natural, and drained microcosms, respectively (Figure 10A). Soluble polyphenol gradually increased under all treatments with the restored site having the highest concentrations (Figure 10B). Labile polysaccharide did not change temporally (Fig. 10C), nor...
did water-extracted dissolved organic carbon (DOC) (data not shown). Phenol oxidase activity, which controls phenol levels, was different among sites and decreased slightly over the drought experiment (Figure 10D). DOC in leachate came mainly from aromatic organic carbon as shown by measurements of absorbance at 280 nm, which explained about 95% of DOC variation (Wang and Richardson 2013). Soluble polyphenol contributed between 5.6 to 38.8% of DOC.

A test of CO₂ emissions over the 60 day drought experiment showed that reduced CO₂ fluxes resulted mainly from the microbial inhibition due to higher peat phenolic content (Figure 11), which might also block CH₄ and N₂O production. Correlation analysis showed that CO₂ emission was only significantly related to soluble polyphenol (negative, r² = 0.694, P < 0.0001, n = 18) and inorganic nitrogen (positive, r² = 0.449, P < 0.001, n = 18) during the initial 60-days incubation (Figure 11). Stepwise regression—including soil water content, labile polysaccharide, phenol oxidase activity, polyphenol and inorganic nitrogen as variables—showed that soluble polyphenol was the main regulator, which accounts for about 70% of the variation of CO₂ flux in this experiment.

Table 1. Properties of Soil and Plants in the Pocosin Study Sites at PLNWR in Coastal NC

<table>
<thead>
<tr>
<th></th>
<th>Natural site</th>
<th>Drained site</th>
<th>Restored site</th>
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</thead>
<tbody>
<tr>
<td>pH</td>
<td>3.7±0.0⁠a</td>
<td>4.3±0.1⁠b</td>
<td>3.9±0.01⁠b</td>
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<tr>
<td>LOI (%)</td>
<td>95.7±0.6⁠a</td>
<td>92.0±1.2⁠b</td>
<td>96.3±0.7⁠a</td>
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<tr>
<td>Total N (%)</td>
<td>1.5±0.1⁠a</td>
<td>1.2±0.1⁠b</td>
<td>1.3±0.1⁠ab</td>
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<tr>
<td>Total C (%)</td>
<td>53.4±1.0⁠a</td>
<td>53.1±0.8⁠a</td>
<td>56.0±1.1⁠a</td>
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<tr>
<td>Total P (µg g⁻¹)</td>
<td>327.2±25.3⁠a</td>
<td>378.1±45.2⁠a</td>
<td>395.6±54.9⁠a</td>
</tr>
<tr>
<td>NOₓ-N (µg g⁻¹)</td>
<td>7.6±1.0⁠b</td>
<td>16.3±3.1⁠a</td>
<td>13.0±0.9⁠ab</td>
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<tr>
<td>NH₄⁺-N (µg g⁻¹)</td>
<td>87.1±21.5⁠a</td>
<td>45.8±8.1⁠ab</td>
<td>4.1±1.7⁠b</td>
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<tr>
<td>C/N in leaves</td>
<td>48.7±4.2⁠a</td>
<td>29.3±3.2⁠b</td>
<td>51.1±3.3⁠a</td>
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<tr>
<td>C/N in stems</td>
<td>135.6±10.7⁠a</td>
<td>75.9±14.4⁠b</td>
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<td>Phenolics (mg C g⁻¹)</td>
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<td>14.9±1.0⁠b</td>
<td>63.3±6.1⁠a</td>
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</table>
The relationship between water level and soluble polyphenol when assessed for our field plots also showed a clear threshold related to water levels (data not shown). Soluble polyphenol increased significantly when water tables dropped to -80 cm and below. Moreover, CO₂ emissions rates were primarily related to both phenolics and water level at our drained site. This provides further evidence that water table and phenolics work together to help control C fluxes.

**Proposed Multi-level Biofeedback Decomposition Control Model**

Given our microcosm responses (Wang and Richardson, 2013) and the field results to-date on different hydrologic, peat quality chemistry, and plant environments found in shrub peatlands in NC, we propose a new biofeedback peat decomposition C control model. Here peat carbon quality is regulated by three biochemical factors: Aromatic compounds (mainly phenolics), black carbon (biochar and aromatics etc.) and lignin complexes (Figure 12), which we postulate are the core biochemical controls on decomposition, whose overall content is primarily regulated by biotic and abiotic factors—hydrology (soil moisture) controls on plant communities, and native plant species production of phenolics, and low-intensity fires which produce and concentrate more phenolic and aromatic carbon, chemical species which greatly impede microbial and fungal decomposition activity (Fenner and Freeman 2011, Podgorski et al., 2012).
Fig. 11. CO$_2$ emission versus (A) soluble polyphenol (phenolics) and (B) inorganic nitrogen (NH$_4^+$ + NO$_3^-$) during the 60-day drought incubation of all peat monoliths taken from pocosin peats in PLNWR in coastal North Carolina (Wang and Richardson 2013).

Fig. 12. A model of the interaction of hydrology, fire, and native species controls on peat/litter quality, microbes and enzymatic activity. These dominant control factors work together to regulate decomposition and carbon sequestration in SE peatlands.
We postulate that the native plant species in STPs - having adaptations for fire dependent life strategies and high water use efficiency - contain high phenol with low nutrients. Thus, their litter is highly resistant to decomposers. Fire under wet or moist soil conditions is important for not only maintaining the native shrub/tree community, but also for producing substantial black carbon (mostly partly burned wood material), which also contains high amounts of aromatic and phenol compounds (Knicker 2007) thus allowing for peat accumulation. Importantly, fire is unlikely to burn peat in saturated peatlands (Turetsky et al. 2011). Thus, management of hydrology and fire intensity in natural and degraded shrub/tree peatlands will be principle to maintaining peat/litter quality (phenol/black carbon), enhancing long-term carbon accumulation and preventing downstream DOC and N losses to coastal waters.

Project Milestones

In our three year study we have nearly completed a C budget for our pocosin sites and we have developed a model of what factor controls C sequestration, which is based on hydrologic conditions, peat quality and native vegetation aromatic chemistry. We plan to continue monthly measurements of GHG losses at PLNWR as well as complete our budgets for C sequestration and losses in 2013. With this extensive database we will develop predictive indices for hydrologic water management levels and phenolic controls on carbon losses and storage. Field data paired with microcosm hydrologic experiments will allow for full development of our predictive models and indices for hydrologic and plant species management for optimizing carbon sequestration and GHG flux rates, the scientific basis needed for development of carbon credits for restored peatland and natural areas. A manuscript (Wang and Richardson) on our microcosm research entitled “Polyphenol buildup inhibits carbon losses in unsaturated peatlands under drought” has been submitted for publication. A second manuscript entitled “Biogeochemical & Vegetation Controls on Carbon Storage & GHG Losses in SE Pocosin Peatlands” is scheduled to be completed in the summer of 2013. Dr. Richardson gave a presentation entitled “Hydrologic and Biogeochemical Controls on Carbon Sequestration in Southern Coastal Freshwater Peatlands” at the annual SWS meetings in Duluth Minnesota in June of 2013. Dr. Richardson gave a presentation entitled “Biogeochemical & Vegetation Controls on Carbon Storage & GHG Losses in SE Pocosin Peatlands: Do Drought and Drainage Really Matter?” at the August 2013 ESA meeting in Minneapolis Minnesota. Drs. Wang, Ho and Richardson gave a poster at the August 2013 ESA meeting in Minneapolis Minnesota entitled “Heavy Precipitation Triggers pulse N\textsubscript{2}O emissions with high N\textsubscript{2}O/N\textsubscript{2} ratios from drained and/or climatic drought stressed peatlands”. A manuscript on this poster is now being prepared.

References


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