



Hydrology and microtopography control carbon dynamics in wetlands: Implications in partitioning ecosystem respiration in a coastal plain forested wetland



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ABSTRACT

Wetlands store a disproportionately large fraction of organic carbon relative to their areal coverage, and thus play an important role in global climate mitigation. As destabilization of these stores through land use or environmental change represents a significant climate feedback, it is important to understand the functional regulation of respiratory processes that catabolize them. In this study, we established an eddy covariance flux tower project in a coastal plain forested wetland in North Carolina, USA, and measured total ecosystem respiration (R_e) over three years (2009–2011). We evaluated the magnitude and variability of three respiration components – belowground (R_s), coarse woody debris (R_{CWD}), and aboveground plant (R_{agp}) respiration at the ecosystem scale, by accounting microtopographic variation for upscaling and constraining the mass balance with R_e . Strong hydrologic control was detected for R_s and R_{CWD} , whereas R_{agp} and R_e were relatively insensitive to water table fluctuations. In a relatively dry year (2010), this forested wetland respired a total of about 2000 g CO₂-C m⁻² y⁻¹ annually, 51% as R_s , 37% as R_{agp} , and 12% as R_{CWD} . During non-flooded periods R_s contributed up to 57% of R_e and during flooded periods R_{agp} contributed up to 69%. The contribution of R_s to R_e increased by 2.4% for every cm of decrease in water level at intermediate water table level, and was nearly constant when flooded or when the water level more than 15 cm below ground. The contrasting sensitivity of different respiration components highlights the need for explicit consideration of this dynamic in ecosystem and Earth System Models.

1. Introduction

Natural wetland soils contain a large amount of carbon that has accumulated over millennia. Permanently or intermittently flooded conditions result in low decomposition rates of organic matter, by which the historic mean residence time of carbon in wetland soils has been estimated as exceeding 500 years (Chmura et al., 2003; Gorham, 1991; Raich and Schlesinger, 1992). Therefore, wetlands are viewed as important long-term carbon sinks (Bridgman et al., 2006; Mitsch et al., 2013). Recently, there has been a growing awareness that changes in climate and land use may alter wetland carbon source-sink

relationships. Sea level rise, high-energy waves and flooding associated with extreme storm events accelerates coastal wetland soil erosion, threatening these globally important stores of carbon (Webb et al., 2013). Further, the conversion of wetlands to agriculture and other land uses can in short time undo millennia of carbon accumulation by promoting conditions favorable for aerobic decomposition (Armentano and Menges, 1986; Armentano, 1980; Laiho, 2006). Conversely, the current efforts at wetland restoration could help mitigate the rising atmospheric carbon dioxide (Craft et al., 1999). Unfortunately, the sensitivity of carbon dynamics to environmental change is much less well investigated in wetlands than in uplands, which limits our ability to

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quantify their future role in the global carbon cycle. Importantly, due to the scarcity of data, wetlands are still absent in most regional and global scale carbon assessments (Battin et al., 2009; Davidson, 2010; Luyssaert et al., 2007; Mahecha et al., 2010).

Compared to upland ecosystems, carbon cycling in wetlands is strongly affected by hydrology in addition to temperature and associated with microtopography (Ehrenfeld, 1995; Jones et al., 1996; Van der Ploeg et al., 2012; Waddington and Roulet, 1996). Together, they determine substrate availability to soil microbial communities, the growth status of plants and the potential upscaling bias of carbon pools and fluxes (Alm et al., 1997; Frei et al., 2012; Kreuzwieser and Rennenberg, 2014; Miao et al., 2013). Although microtopographic and hydrologic variations are common characteristics in wetlands (Barry et al., 1996; Burke et al., 1999; Nungesser, 2003; Riutta et al., 2007), linking these two key factors with carbon dynamics quantitatively has been a great challenge due to the difficulties in field data collection and not been well addressed. Studies in some restored wetlands have shown significant effects of microtopography and hydrology on soil and vegetation, providing insights of how carbon dynamics might be affected in natural systems (Barry et al., 1996; Bledsoe and Shear, 2000; Bruland and Richardson, 2005).

Ecosystem respiration (R_e) is a key process that regulates the role of an ecosystem as carbon source or sink (Grace and Rayment, 2000; Valentini et al., 2000). R_e integrates a variety of autotrophic and heterotrophic processes, every component of which may exhibit different sensitivities to changes in environmental conditions (Bahn et al., 2010; Davidson and Janssens, 2006; Hopkins et al., 2013; Teskey et al., 2008; Trumbore, 2006), making the investigations into respiration complex and challenging. This is particularly true in wetlands, where variable hydrology may have contrasting effects on different respiratory components (Lafleur et al., 2005). In the short term, belowground respiration (R_s) usually decreases immediately upon flooding due to the resistance of water on gas diffusion, of which the coefficient is 10,000 times smaller than in the air (Denny, 1993). Previously, we observed that during a rainfall event, when some microsites turned inundated, R_s decreased rapidly from more than $5 \mu\text{mol CO}_2\text{-C m}^{-2} \text{s}^{-1}$ to less than $0.5 \mu\text{mol CO}_2\text{-C m}^{-2} \text{s}^{-1}$ within two hours (Miao et al., 2013). Direct measurements on response of plant respiration to change in hydrologic regimes are rare, but many studies indicated that plant organs respond slowly to temporary or continuous flooding (from days to years), especially for flood-tolerant species (Anderson and Pezeshki, 2001; Keeland et al., 1997; Kreuzwieser and Rennenberg, 2014), because aboveground plant tissues are still exposed to adequate oxygen and respiration could use plant carbon storage or current photosynthates (Chapin et al., 1990).

The long-term effect of permanent or intermittent flooding, which favors peat accumulation but limits plant growth, may have been to store more carbon in soils than in wetland plants (Bridgman et al., 2006; Gorham, 1991). It appears that due to different carbon storage between pools and driver sensitivities of respiratory components, the ratios of these component fluxes to R_e differ by ecosystem type (Aerts, 1997; Davidson et al., 2006; Harmon et al., 2004). For example, boreal and temperate upland ecosystems generally store large amounts of carbon in both plants and soils, and R_s contributes to R_e comparable to plant respiration, with the R_s/R_e ratio reported at 0.4–0.8 (Janssens et al., 2001; Lavigne et al., 1997; Law et al., 1999). Tropical rainforests accumulate larger amounts of carbon in plants than in soils compared to higher latitude forests, resulting lower contribution of R_s to R_e with a ratio of 0.3–0.4 (Chambers et al., 2004; Saleska et al., 2003). Associated with the live plant components, plant debris also contribute differently between ecosystems. It was predicted that the decomposition of coarse woody debris (CWD, R_{CWD}) in a central Amazon forest could be 65–88% of total carbon loss (Chambers et al., 2001), whereas in some loblolly pine plantations in the Southeastern US it was reported to be only 20% (Noormets et al., 2012). Given the unique carbon storage in wetlands and the hydrologic effects on respiratory components, one would expect

a different pattern of the ratios of respiratory components to R_e in wetlands. For example, in a forested wetland, soil might contribute similarly to or more than plants to R_e during non-flooded periods, while plant respiration might dominate during flooded periods.

To our knowledge, rigorous partitioning of R_e to its primary components has rarely been done in wetlands, and hydrology and microtopography are yet rarely taken into account in upscaling. The current study was designed to fill this gap. Specifically, we investigated a forested wetland in the coastal plain of the Southeastern US, where the majority of the forested wetlands in the US are located. These southern forested wetlands offer important values to the society, such as removing and transforming inorganic nutrients from the water column to improve the water quality, and providing a source of fixed carbon and organic nutrients to aquatic organisms that maintains productivity of aquatic ecosystems downstream (Walbridge 1993). These systems also face the threat of sea level rise as well as the conflict between conservation and development (Dugan 1993). A comprehensive understanding of the biogeochemical functions that these important functions are based upon is therefore urgently needed to better manage these ecosystems, especially under the changing climate and land use.

The objectives of the current study were to understand the ecosystem-scale CO_2 efflux from a forested wetland by (1) characterizing the seasonal variations of R_e and its three components – R_s , R_{CWD} and aboveground plant respiration (R_{agg}) and hydrologic effects on these seasonal variations; (2) partitioning R_e into R_s , R_{CWD} , and R_{agg} at monthly and annual scales, and (3) quantifying hydrologic effects on the contribution of component fluxes to R_e . In addition, we discussed the uncertainties of carbon budget closure related to different measuring techniques and resultant bias. Overall, based on a careful upscaling and budget estimate, this study attempts to provide a better understanding of the special characteristics of forested wetlands related to hydrologic variations and information for improving models of biogeochemical processes in wetlands.

2. Methods

2.1. Site description

The study area is located at the Alligator River National Wildlife Refuge (ARNWR), on the Albemarle-Pamlico peninsula of North Carolina, USA ($35^{\circ}47'N$, $75^{\circ}54'W$, Fig. 1a). The site was established in the middle of the peninsula in November 2008, including a 35-m instrumented tower for eddy covariance (EC) flux measurements and micrometeorology above the canopy. A ground micrometeorological station was located about 30-m away from the flux tower, and 13 vegetation plots spread over a 4 km^2 area were distributed across the site (Fig. 1a).

The mean annual temperature and precipitation from climate records of an adjacent meteorological station (Manteo AP, NC, $35^{\circ}55'N$, $75^{\circ}42'W$, National Climatic Data Center) for the period 1981–2010 are 16.9°C and 1270 mm, respectively. The forest type is mixed hardwood swamp forest; the overstory is predominantly composed of deciduous species – black gum (*Nyssa sylvatica*), swamp tupelo (*Nyssa biflora*) and bald cypress (*Taxodium distichum*), with occasional red maple (*Acer rubrum*), and evergreen species – Atlantic white cedar (*Chamaecyparis thuyoides*) and loblolly pine (*Pinus taeda*); the understory is predominantly fetterbush (*Lyonia lucida*), bitter gallberry (*Ilex glabra*), and red bay (*Persea borbonia*).

The canopy height ranged 15–20 m, and the leaf area index generally peaked in July at 3.5 ± 0.3 (Smith et al., 2008). Aboveground live biomass was estimated allometrically at 37.5 ± 12.5 (mean \pm SD) Mg C ha^{-1} (Jenkins et al., 2004). Coarse woody debris (CWD) stored 3.1 ± 2.0 (mean \pm SD) Mg C ha^{-1} (Waddell 2002). The major soil series are poorly drained Pungo and Belhaven mucks, whose organic carbon content is approximately 40–100% and 20–100%, respectively (Web Soil Survey accessed on 14 December 2009). Dry soil

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