LINKING FRESHWATER TIDAL HYDROLOGY TO CARBON CYCLING IN BOTTOMLAND HARDWOOD WETLANDS

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Abstract—Hydrology is recognized as one of the principal factors regulating soil biogeochemical processes in forested wetlands. However, the consequences of tidally mediated hydrology are seldom considered within forested wetlands that occur along tidal water bodies. These tidal water bodies may be either fresh or brackish, and the tidal streams function as a reservoir to sustain a shallow water table depth as compared to nontidal stream reaches. Accordingly, both the hydrology and water chemistry are expected to affect the forest carbon cycle; however, there are few studies to support this assertion. Hypotheses that are suggested by this hydrogeomorphic setting include greater net primary productivity and greenhouse gas emissions. However, given the persistent and dynamic high water table, it is important to consider micro-topography in quantifying greenhouse gas emissions, a functionality similar to boreal peatlands. A major constraint to assessing carbon cycle dynamics in tidally influenced forested wetlands is the lack of an accepted classification system and reliable spatial data base to indicate their spatial extent; this is particularly important for the upper tidal reaches where there is not a threat of changes in salinity associated with sea level rise. Advancing research to address this important part of the landscape is fundamental to addressing issues associated with sea level rise and the interaction of coastal development on estuaries.

INTRODUCTION

Tidal freshwater forested wetlands exist at the interface between marine and terrestrial ecosystems. Until recently, they have been overlooked by wetland scientists, perhaps because they have a hydrologic regime that is characterized by both marine and terrestrial influences. The American Geophysical Union (AGU) Chapman Conference–Hydrogeomorphic Feedbacks and Sea Level Rise in Tidal Freshwater River Ecosystems, held in Reston, VA, 13-16 November, 2012, highlighted the importance of these wetland ecosystems and the considerable uncertainties about their ecological functions, as well as the potential effects associated with sea level rise and climate change. The objective of this paper is to provide context for needed research on the carbon cycle in tidal freshwater forested wetlands because they are at the outlets of terrestrial watersheds that are inextricably linked to estuaries, and it is a landscape that is experiencing sustained development pressures.

Tidal Freshwater Forested Wetlands

Tidal freshwater forested wetlands (TFFW) occur in floodplains situated near the coastal zone along freshwater rivers that are subject to tides. While water table depth and duration of inundation are the primary factors controlling vegetation patterns in wetlands (Rheinhardt and Hershner 1992) along tidally influenced rivers and streams, salinity concentration intercedes and regulates vegetation zonation (Odum 1988). Salt marsh communities dominated by smooth cordgrass (*Spartina alternafloras*) and black needlerush (*Juncus roemarianus*) occur in estuarine riparian zones where salinity levels range from 5 to >30 ppt. In the oligohaline (brackish) marsh (0.5–5 ppt) zone, smooth cordgrass and black needlerush are common, but big cordgrass (*Spartina cynosuroides*) is typically prominent and is often mixed with bulrush (*Scirpus americana*) and pickerelweed (*Pontederia cordata*) (Wiegert and Freeman 1990). The most significant shift in vegetative community composition occurs where salinity concentration is below 0.5 ppt; here, freshwater marsh vegetation includes spatterdock (*Nuphar lutem*), giant cutgrass (*Zizaniopsis miliaceaes*), wild rice (*Zizania aquatica*), smartweed (*Polygonums* spp.), cattail (*Typha* spp.), and rose mallow (*Hibiscus moscheutos*) (Odum and others 1984).

Tidal freshwater forested wetlands exist in a narrow margin between the head of tide and freshwater marsh, and they are distinguished from nontidal forests by the presence of tide in the adjoining stream or river. Tidal freshwater forested wetlands support a broad range of bottomland hardwood communities ranging from bald cypress (*Taxodium distichum*) and water tupelo (*Nyssa*

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aquatic) stands in floodplains that are regularly flooded and maintain nearly constant soil saturation, to oak (*Quercus* spp.) and gum (*Nyssa sylvatica)* stands that are seasonally flooded, closely resembling the nontidal bottomland hardwood communities further upstream (Conner and others 2007, Kroes and others 2007, Light and others 2002).

Distribution and Classification

The presence of salt-tolerant vegetation assists in defining the boundaries between saltwater, brackish, and freshwater vegetative communities, but locating the forested edge of the tidal zone is difficult due to the uninterrupted forest cover within the tidal/nontidal convergence zone (Day and others 2007). This uncertainty arises from multiple sources, including the lack of a well-defined classification system, inconsistent terminology, and lack of data on the head-of-tide. The current estimates of land area occupied by TFFW are based on a coastal county survey conducted by the National Oceanic and Atmospheric Administration (NOAA), which delineated tidal freshwater forests and marshes based on National Wetland Inventory (NWI) data (Field and others 1991). Thus, the estimate is likely conservative due to reliance solely on vegetative data in a system that is hydrologically complex (Doyle and others 2007).

The most commonly used wetland classification system is the U.S. Fish and Wildlife Service's Wetland and Deepwater Habitat Classification System, developed by NWI, which uses vegetative cover to distinguish between wetland types and classes (Cowardin and others 1979). Tidal freshwater forested wetlands are categorized as either riverine (in-channel) or palustrine, which are denoted tidal by a water regime modifier. Tidal freshwater swamps are defined as separate from the adjacent estuary system by a salinity threshold of less than 0.5 ppt, and their proximity to the open ocean. Estuarine wetlands are mostly open or only partially closed off to the ocean, where salinities can range from polyhaline (18–30 ppt) closest to the ocean, to mesohaline (5.0–18 ppt) further up the estuary (Cowardin and others 1979). The riverine classification relates primarily to the area between the banks of a stream channel and describes both in-channel and forested cover. Palustrine forested wetlands include wetlands dominated by trees. Riverine and palustrine classifications also apply to nontidal wetlands; therefore, a water regime modifier is used to denote wetlands subjected to a freshwater tide. In the tidal system, three main types of flooding regimes exist: subtidal, regularly flooded, and irregularly flooded. To avoid confusion with saline environments, the nontidal water regime modifiers are used with the addition of the word "tidal" to differentiate these systems from palustrine or riverine nontidal systems. The modifiers indicate wetland surface tidal inundation patterns and include permanently flooded-tidal (the land surface is exposed less than once daily), regularly flooded-tidal (land surface is exposed at least one time daily), and seasonally flooded-tidal (land surface is flooded less than daily) (Cowardin and others 1979).

The tidal freshwater forested wetlands are most prominent along the Southeastern Atlantic lower Coastal Plain, where it is estimated that over 200,000 ha exist (Field and others 1991). However, considerable uncertainty exists in the estimates of TFFW area, in large part because of the inconsistent use of the tidal modifiers within the NWI. The majority of TFFW are concentrated along the coasts of the South Carolina, Georgia, Florida, Virginia, and Maryland, with smaller areas along the Gulf Coast and upper portions of the Atlantic Coastal Plain. South Carolina has the largest TFFW land area (estimated at over 40,000 ha) as a result of the relatively large tide range and low topographic gradient in the lower Coastal Plain.

DISCUSSION

Hydrology of Tidal Freshwater Forested Wetlands

Riparian wetlands exist at the interface of aquatic and terrestrial ecosystems, which are distinguished functionally by gradients of biophysical conditions, ecological functions, and biological communities (Batzer and Sharitz 2006). Their landscape position provides a hydrologic connection between water bodies and uplands due to proximity to rivers, streams, lakes, and estuary or marine environments. The main sources of water are precipitation, groundwater discharge, overland flow, interflow, and surface runoff from the adjacent water body (Batzer and Sharitz 2006). Riparian wetlands that occupy the freshwater (salinity <0.5 ppt) intertidal zone between nontidal forested riparian zones and freshwater marsh have a hydrologic regime that is subject to both tidal and fluvial influences. Accordingly, the water table in TFFW is affected by the adjoining tidal stream or river and is typically much wetter than upland riparian zones (Hackney and others 2007).

Studying a TFFW riparian zone in the lower Coastal Plain of South Carolina, Czwartacki (2013) showed that the tidal freshwater stream functioned as a reservoir to sustain a higher mean water table within the tidally influenced riparian zone as compared to the nontidal bottomland hardwood wetland (table 1). Accordingly, the tidal stream reach sustains the water table, and during periods of low flow from the uplands (e.g., during summer and fall), the hydraulic gradient can be upstream (fig. 1). In addition to maintaining a higher water table, the hydroperiod within the tidal riparian zone responds to the tidally mediated stream stage, especially within 30–50 m of the stream. Therefore, soil in tidal freshwater bottomland hardwood wetland may be characterized as being much wetter than a nontidal wetland, which suggests that the carbon dynamics would also be affected.

Micro-topography

Micro-topography is the undulating relief that is common to most forests, but particularly pronounced in wetlands, where it is typically described as hummocks and hollows. Hummocks are elevated areas (averaging +15 cm above base soil elevation). In contrast, hollows are bowl-shaped depressions below the average wetland surface elevation, characterized by long periods of saturation that restrict plant growth (Courtwright and Findlay 2011, Duberstein and Conner 2009). Micro-topography affects the available soil volume above the water table (fig. 2). Hollows are thought to increase flood duration and soil moisture through depression storage and affect the frequency and depth of flooding (Courtwright and Findlay 2011). Duberstein and Conner (2009) identified semi-diurnal tide signatures in groundwater hydrographs in old slough channels and found persistently saturated soil conditions despite drought conditions. Rheinhardt

Table 1—Mean water table depth in the tidal transition zone and nontidal bottomland hardwood wetland over a 16-month period in 2011-2013 (from Czwartacki 2013). Sites are arranged on a tidal gradient, with the far left being the lowest tidal site (LLT) and the far right being the nontidal site (NT-1).

Zone	Mean water table depth below surface (cm)
Lower tidal	45
Mid-tidal	108
Upper Tidal	154
Nontidal	154

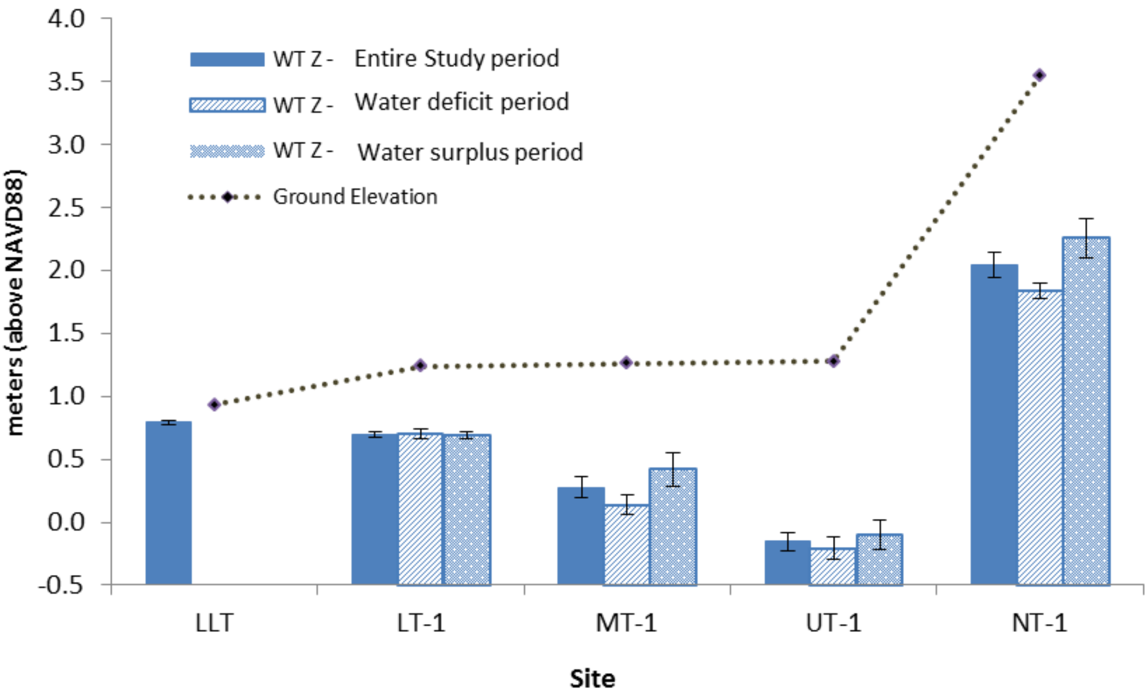

Figure 1—Water table characterization in a tidal to nontidal stream reach, based on results presented by Czwartacki (2013) for Huger Creek, South Carolina.

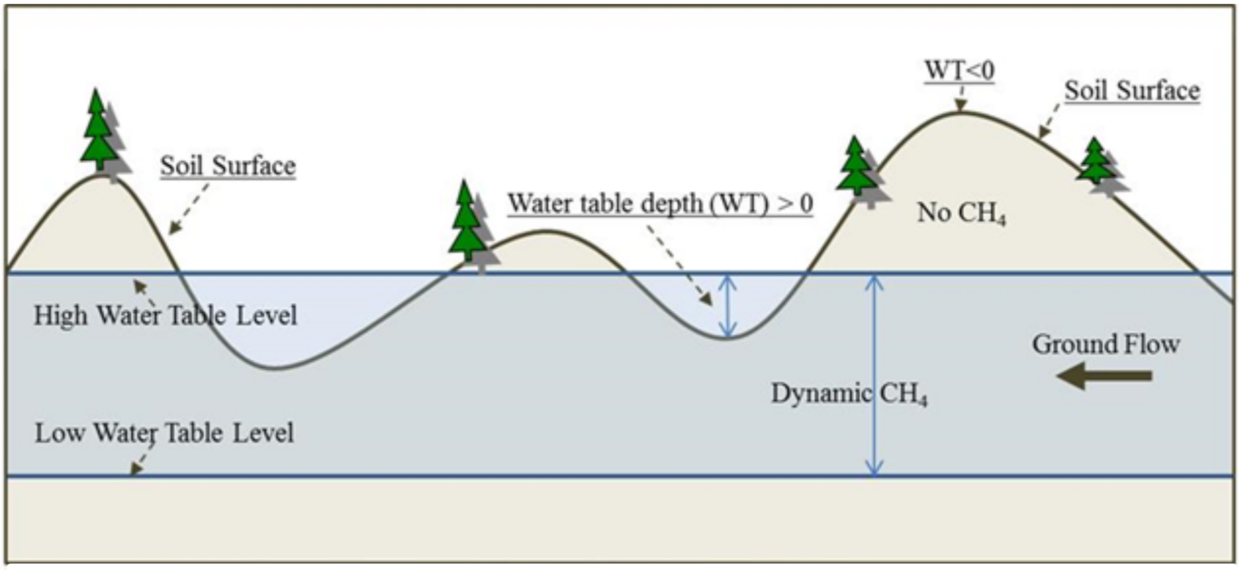

Figure 2—Effect of micro-topography on soil volume.

and Hershner (1992) also reported that the tidal stream hydroperiod influenced the water regime in tidal-swamp hollows along the Pamunkey River, Virginia. In forested peatlands, micro-topography is recognized to affect carbon dynamics and greenhouse gas emissions (Trettin and others 2006). Taking into account that soil water regime is similarly influenced in the mineral soil of tidally influenced swamps, the expectation is that they will also exhibit a spatially complex soil gas emission pattern that is regulated by the distribution of the micro-topography and proximity to the tidal creek.

Carbon Dynamics in Tidal Freshwater Forested Wetlands

Carbon dynamics—and especially greenhouse gas emissions—in forested wetlands are strongly influenced by water table position (Trettin and Jurgensen 2003). Consequently, the contrasting hydrologic setting within tidal and nontidal freshwater riparian zones may be expected to alter carbon sequestration and fluxes (fig. 3). Wetland-dominated riparian zones have long been recognized as a primary source of carbon in waterborne fluxes of carbon in receiving streams (e.g., Doskey and Berch 1994, Harvey and Odum 1990, Harvey and others 1995). Although riparian soils are assumed to be the primary source of dissolved carbon compounds in adjacent receiving waters, more recent studies indicate that "fresh" vegetation decomposition products can make up the majority of dissolved organic carbon compounds found in tidally influenced stream channels (Engelhaupt and others 2001). Waterborne carbon transport and atmospheric losses in wetland-dominated riverine systems have been found to be dominated by dissolved inorganic carbon (DIC) transport and subsequent atmospheric loss through abiotic and/or microbial mediated processes (Elder and others 2000, Richey and others 2002.)

The freshwater tidal stream functions as a reservoir of water that oscillates on a semidiurnal tidal cycle. During each semidiurnal tidal cycle, channels and rivulets within the riparian zone are inundated and subsequently drained, with the tidal stream being the source of the flood water and the receiving stream for the draining water. Correspondingly, there is a direct exchange of pore water in sediments within 2–3 m of the tidal stream (Nuttle and Hemond 1988), suggesting that dissolved constituents, including dissolved carbon and gases, and inorganic constituents are also exchanged. In many estuarine systems, there can be large changes in flow and water level on the tidal time scale (<13 hours); but, on extended time scales (day to weeks), there may be only small changes in net (tidally averaged) flow and water level during periods of low runoff from the uplands. In tidal creeks, like Huger Creek where there is seasonal freshwater flow from the uplands, the streamflow can be dominated by tidal inflows on the flood (incoming) and ebb (outgoing) tides during periods of low flow from the uplands. However, during periods of high flow from the uplands, flow from within the watershed may dominate the stream discharge. During low- or no-flow upland conditions, net flows will be negative (inland) with downstream source water, with a different water-quality signature, slowly moving upstream and exchanging with the upland water in the channel and riparian pore water. The residence time of downstream source water in these upper tidal reaches can last for long periods of time during drought periods, with high freshwater outflows required to flush the system to a more riverine-type condition.

In nontidal wetlands, methane (CH_4) efflux is regulated by the water table relative to the soil surface (Trettin and others 2006), with hummock positons having significantly lower emission rates than hollows (Bubier and others 1993). Studying a bottomland tidal swamp in North Carolina, Megonigal and Schlesinger (2002) showed that tidal forcing on the riparian zone water table can regulate CH_4 efflux from hollows. Accordingly, the net flux across an area of tidal riparian zone is likely an interaction among micro-topography and tidal forcing.

PERSPECTIVE

As a result of the high evapotranspiration demands of coastal forests (Amatya and Skaggs 2011, Domec and others 2012, Gholz and Clark 2002, Marion and others 2013), many headwater watersheds exhibit ephemeral flow, being dry during the most of the growing season and having runoff in the fall or winter. Thus, the hydrologic flux from these upland watersheds and their associated riparian zones occurs in pulses during precipitation-driven flow events (Dai and others 2011, 2013; Epps and others 2013). In contrast, the tidal riparian reaches that occur lower in the landscape experience daily pulses of flooding and ebbing (rising and draining) waters, which can effectively import carbon and other constituents, as well as export materials from these riparian zones. The fluxes and associated mass balance of carbon within these forested wetlands that interface uplands and estuaries have not been measured. We hypothesize that carbon sequestration is higher in TFFWs as compared to an upstream nontidal forested wetland, and that carbon export is also larger (fig. 4). In tidally influenced riparian zones, available water should not limit productivity as compared to nontidal riparian zones that exhibit wide fluctuations in water table depth; correspondingly, export of organic matter will be facilitated by the daily inundations from the tidal stream.

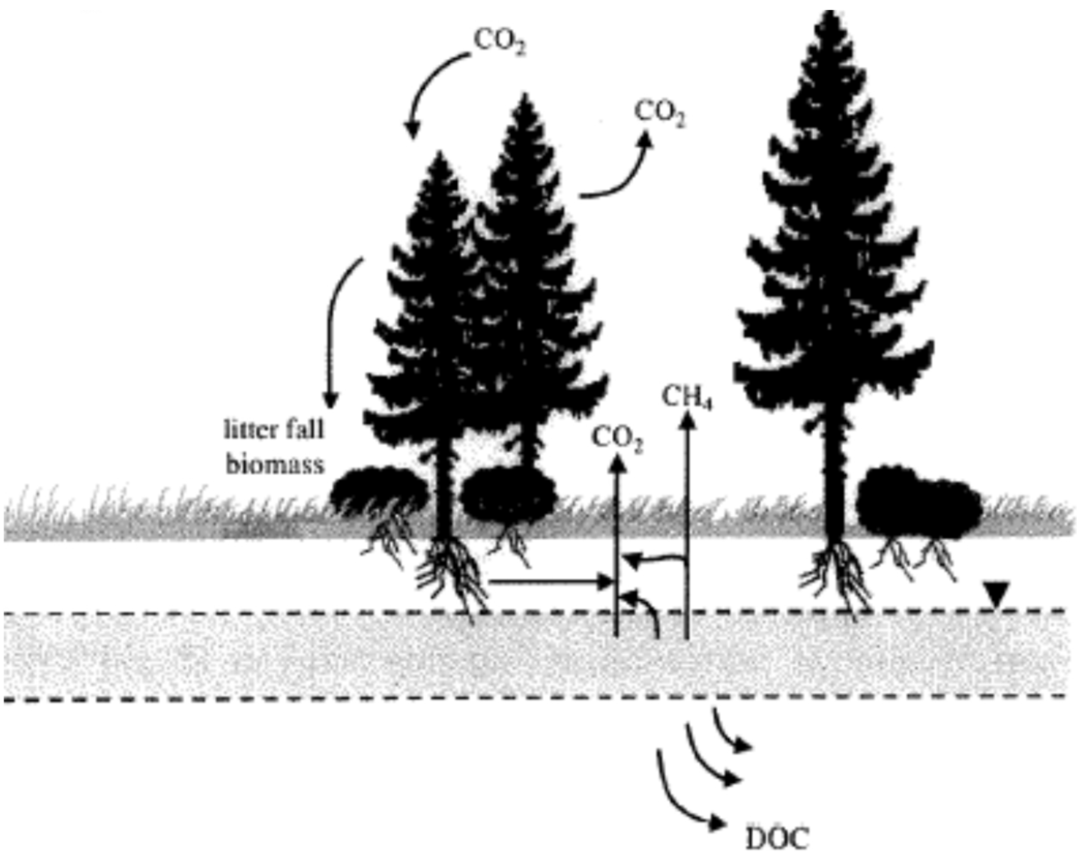

Figure 3—Carbon cycle forested wetlands (adapted from Trettin and Jurgensen 2003) reflecting a nontidal and tidal hydrologic regime.

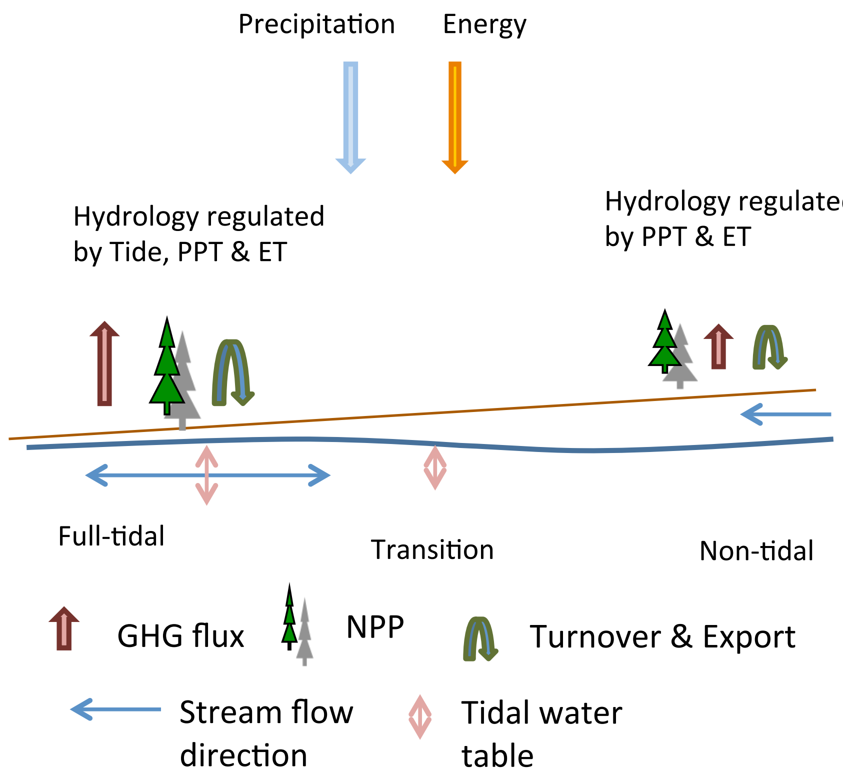

Figure 4—Depiction of the effects of the tidally imposed hydrologic regime on carbon cycling. Sequestration, turnover and greenhouse gas emissions are expected to be greater in the tidal freshwater forested wetland as compared to the upstream nontidal wetland principally due to the persistent high water table.

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