Landscape Ecol
DOI 10.1007/s10980-012-9758-8

RESEARCH ARTICLE

Wetlands, carbon, and climate change

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Received: 3 December 2011 / Accepted: 7 May 2012

Abstract Wetland ecosystems provide an optimum natural environment for the sequestration and long-term storage of carbon dioxide (CO_2) from the atmosphere, yet are natural sources of greenhouse gases emissions, especially methane. We illustrate that most wetlands, when carbon sequestration is compared to methane emissions, do not have 25 times more CO_2 sequestration than methane emissions; therefore, to many landscape managers and non specialists, most wetlands would be considered by some to be sources of climate warming or net radiative forcing. We show by dynamic modeling of carbon flux results from seven detailed studies by us of temperate and tropical wetlands and from 14 other wetland studies by others that methane emissions become unimportant within 300 years compared to carbon sequestration in wetlands. Within that time frame or less, most wetlands become both net carbon and radiative sinks. Furthermore, we estimate that the world's wetlands, despite being only about 5–8 % of the terrestrial landscape, may currently be net carbon sinks of about 830 Tg/year of carbon with an average

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of 118 g-C m^{-2} $year^{-1}$ of net carbon retention. Most of that carbon retention occurs in tropical/subtropical wetlands. We demonstrate that almost all wetlands are net radiative sinks when balancing carbon sequestration and methane emissions and conclude that wetlands can be created and restored to provide C sequestration and other ecosystem services without great concern of creating net radiative sources on the climate due to methane emissions.

Keywords Carbon dioxide · Carbon sequestration · Marsh · Methane · Methanogenesis · Peatland · Swamp · Global carbon budget

Introduction

Wetlands offer many ecosystem services to humankind, including water quality improvement, flood mitigation, coastal protection, and wildlife protection (Mitra et al. 2005; Mitsch and Gosselink 2007). It is estimated that 20–30 % of the Earth's soil pool of 2,500 Pg of carbon (Lal 2008) is stored in wetlands (Roulet 2000; Bridgham et al. 2006), although wetlands comprise only about 5–8 % of the terrestrial land surface (Mitsch and Gosselink 2007). Because of their anoxic wet conditions, wetlands are optimum natural environments for sequestering and storing carbon from the atmosphere.

It is also estimated that wetlands emit 20–25 % of current global methane emissions, or about 115–227 Tg-CH_4 $year^{-1}$ (Whalen 2005; Bergamaschi et al. 2007; Bloom et al. 2010). Rice paddies account for about 60–80 Tg-CH_4 $year^{-1}$ of methane emissions. The tropics may account for 52–58 % of the wetland emissions (Bloom et al. 2010).

The standard global warming potential (GWP_M) used by the international panel on climate change (IPCC 2007) and others to compare methane and carbon dioxide is now 25:1 over 100 years. This GWP ratio is used by policy makers to compare methane and carbon dioxide fluxes. Whiting and Chanton (2001), Fuglestvedt et al. (2003) and Frolking et al. (2006) all expressed concern about using a constant methane GWP factor because: (1) a longer period (100–500 years) should be considered for sustainable ecosystems such as wetlands (necessitating a dynamic modeling approach); and (2) since GWPs are constructed to express equivalence in terms of the radiative forcing over a chosen time horizon of pulse emissions of different gases, the GWP does not consider persistent sources and sinks well.

A study of North American carbon fluxes proposed that wetlands probably do not have either a net radiative balance or forcing on climate significantly different from zero because of a general balance between carbon sequestration and methane emissions, but "large CH_4 emissions from conterminous US wetlands suggest that creating and restoring wetlands may increase net radiative forcing…" (Bridgham et al. 2006).

Here we present original results on the balance between soil carbon sequestration and methane emissions from seven temperate and tropical wetlands and develop a dynamic model simulating the net radiative forcing and carbon exchange of these wetlands with the atmosphere, assuming the GWP of 25 on methane as a model assumption. The model is then applied to 14 more wetlands from tropical, temperate, and boreal regions to evaluate the net radiative forcing and carbon exchange for a wide variety of sites. We estimating the net carbon retention by wetlands on a global scale from these studies and from recent estimates of the global extent of wetlands.

Materials and methods

Our investigation first measured carbon accumulation in soils and methane emissions at seven created and natural wetlands located at six wetland sites in the temperate zone and tropics.

Site descriptions

Created flow-through temperate marshes—Two 1-ha wetlands were created in 1993–1994 at the Wilma H. Schiermeier Olentangy River Wetland Research Park (ORWRP) on the campus of The Ohio State University (40°1′12″N; 83°1′7″W). The ORWRP is located at the eastern-most edge of the Central USA Plains portion of the eastern temperate forest ecological region (Biome) of North America. The original non-hydric alluvial soil type at the site, the Ross series (Rs), developed strong hydric indicators within a few years of pumped flooding, which started in March 4 1994, from the Olentangy River, a third-order stream in the agriculturally dominated Scioto River watershed in central Ohio. Water from the river is pumped continuously to these wetlands according to a formula relating pumping rates to river stages. The western basin, Wetland 1, was planted with 13 native species of macrophytes in May 1994, while the eastern basin, Wetland 2, was allowed to colonize naturally (Mitsch et al. 1998). The function of the two wetlands has been frequently compared since their creation in 1994 (Mitsch et al. 1998, 2005, 2012).

Natural flow-through temperate wetland—Old Woman Creek Wetland (41°22′38″N; 82°30′48″W), a 56-ha flow-through marsh discharging into Lake Erie, is located in northern Ohio adjacent to Lake Erie (Mitsch and Reeder 1991; Bernal and Mitsch 2012). The wetland receives water from the 69-km^2 agricultural watershed and occasional seiches when the sand barrier between the wetland and Lake Erie is broken, allowing lake water flow into the wetland. Dominant plant communities at Old Woman Creek include *Nelumbo lutea*, *Typha* spp., *Scirpus fluviatilis*, and *Phragmites australis*.

Tropical wetland slough—This tropical wetland (112 ha), located on the campus of EARTH University in the Caribbean lowlands of eastern Costa Rica (10°13′0″N; 83°34′16″W), is a slow-velocity slough within a disturbed humid tropical forest area undergoing natural restoration after years of grazing. The climate is humid, with a 10-year precipitation average of 3,463 mm/year. The wetland is dominated by water-tolerant species, e.g. *Spathiphyllum friedrichsthalii*, *Dracontium* sp., *Raphia taedigera*, and *Calathea crotalifera*, with surrounding hardwood trees and palms, e.g., *Pentaclethra macroloba*, *Terminalia oblonga*, *Chamaedorea tepejilote*, *Virola koschnyi*, and *Virola sebifera* (Mitsch et al. 2008). Several large rivers, most notably the Parismina River, run through the campus, flooding the area and feeding the creeks that maintain the wetland continuously flooded. Soils are poorly drained alluvial Aquepts on flat relief, and feature a thick layer of floating mucky peat, due to high vegetative productivity, slow-decomposition, and high water table (Bernal and Mitsch 2008).

Tropical rain forest isolated wetland—La Selva wetland (3 ha; 10°25′49″N; 84°0′37″W) is located in a tropical rain forest within La Selva Biological Research Station at the confluence of the Puerto Viejo and the Sarapiqui Rivers. The site receives an average of 4,639 mm year^{-1} of precipitation. The rain forest is dominated by canopy, subcanopy, and understory tree species, such as *Anaxagorea crassipetala*, *Pentaclethra macroloba*, and *Rinorea deflexiflora* (King 1996). The wetland is a relatively open canopy area and hosts large stands of *Spathiphyllum friedrichsthalii* and the grass *Gynerium sagittatum*, in addition to smaller stands of *Asterogyne martiana* near the edges. The wetland soils at La Selva have been identified as Tropaquepts. High year-round precipitation drives the wetland hydrology, but high temperatures and evapotranspiration rates maintain standing water for only 3–5 days after major precipitation events.

Seasonally wet tropical floodplain—Palo Verde wetland (1,200 ha; 10°20′37″N; 85°20′33″W) is a seasonally flooded floodplain freshwater marsh in western Costa Rica that experiences distinct wet and dry seasons due to both rainfall and occasional river flooding from the Tempisque River. The site receives 1,248 mm year^{-1} of rainfall during the rainy season (May–October). Floating aquatic and emergent plants such as *Eichhornia crassipes*, *Thalia geniculata*, and *Typha domingensis* dominate the permanent and saturated ponds during the wet season, whereas in the dry season grasses and sedges, such as *Eleocharis* sp., *Cyperus* sp., *Paspalidium* sp., *Paspalum repens*, and *Oxycaryum cubense* dominate (Crow 2002). The wetland soils are Vertisols. The wetland hydrology is largely influenced by wet season's precipitation and watershed runoff, with occasional flooding from the Tempisque River when its water level overflows the sediment barrier created between the river and the wetland. This marsh has been heavily managed by cattle grazing and farm tractor crushing of plants have been used to control *Typha domingensis* with modest success (Trama et al. 2009).

Tropical seasonally flooded inland delta—The Okavango Delta in Botswana is a 12,000 km^2 (total flooded area during average years) to 15,000 km^2 (total area inundated during extremely wet years) tropical freshwater wetland/upland complex in the semi-arid Kalahari Basin of northern Botswana, Africa. Ecosystems in the Okavango include non-flooded uplands, seasonally flooded floodplains (which are mostly dominated by grasses and sedges rather than woody species) and stream channels. The permanently flooded floodplain is dominated by hydrophytes (Ramberg et al. 2006, 2010), such as *Cyperus articulatus*, *Oryza longistaminata*, *Panicum* sp., and *Schoenoplectus corymbosus*, among others. The overall water budget for the Okavango Delta shows an average of 550 mm/year of water entering the Delta area from the Okavango River and a similar amount of precipitation (490 mm/year) occurring through the year (Mitsch et al. 2010). Almost all of the water that comes in by rainfall or river flooding is lost in evapotranspiration in both the floodplains and uplands of the Delta. The peak river flow at the inflow to the Delta occurs in March through May, after the rainy season, while the highest water level in the floodplain occurs between July and September. Our research study site within the Okavango (19°32′29″S; 23°9′58″E) was a combination of permanently flooded and intermittently flooded marshes and stream-side vegetation.

Field and laboratory methods

Carbon sequestration

Soil cores were extracted from each wetland in Ohio, Costa Rica, and Botswana according to methods described by Anderson et al. (2005) and Bernal and Mitsch (2012). In the natural wetlands, accretion rates in the soil were determined non-destructively with ^{137}Cs and ^{210}Pb activity (pCi, 10^{-12} Ci) in each 2-cm increment soil sample by gamma spectrometry using a high efficiency germanium detector (Canberra, GL 2820R). This method has been applied successfully in several wetland sites (e.g., Graham et al. 2005; Craft 2007; Bernal and Mitsch 2012). Soil carbon sequestration was then calculated as the soil carbon pool to the depth where the ^{137}Cs peak was identified and assumed to be a marker for 1964. Soil carbon pool was determined by measuring soil carbon content with a Total Carbon Analyser (Shimadzu, SSM-5000A). In each natural wetland, three cores were composited in each of the three distinct vegetation communities present (9 cores per wetland) to account for heterogeneity of the wetlands (Ilus and Saxén 2005).

In the created wetlands in Ohio, specific soil testing prior to wetland construction in 1993 revealed highly compactable subsurface soils (50–300 cm below surface) that were grey silty-clay, with low permeability. This antecedent soil has remained very distinguishable from the less cohesive sediment layer accumulating above it after the wetland was created (Anderson et al. 2005), serving as a horizontal marker to estimate sediment accretion throughout both wetlands. Sediment sampling occurred in May 2004 and May 2009 (10 and 15 years after these wetlands were created, respectively) using a 10-m grid system established in 1993. Cores were extracted and used to measure sediment depth (from surface to antecedent soil surface) at a total of 127 grid points, providing an even spatial distribution throughout the two wetlands. In 2009, forty-four sediment cores (from 10 to 35 cm deep), divided in 5 cm increments were analyzed for carbon content and bulk density. Mean carbon sequestration was estimated for the open water, emergent, and edge plant communities of each wetland, and total carbon sequestration of each wetland was weighted for relative cover percentage on vegetated and open cater communities.

Methane emissions

Non-steady state gas-sampling chambers were used to sample methane emissions at the six wetland sites according to methods described by Altor and Mitsch (2006, 2008) and Nahlik and Mitsch (2010, 2011). The Costa Rican wetlands (three sites) were sampled six times over a 2.5-year period while the Ohio wetlands (three wetlands at two sites) were sampled five to seven times over a 2-year period to include all seasons. The tropical Botswana site was sampled once. Each sampling consisted of morning and evening sampling, which were then averaged for a daily mean methane emission rate. Six pairs of permanent chambers were used at each wetland site. Included in these six pairs were two, permanently flooded sites, two edge (intermittently flooded) sites. And two adjacent upland sites used as controls. Soil, water, and chamber air temperatures and water depth were recorded at each chamber. Collected gas samples were stored at 4 °C in the laboratory and analyzed within 28 days for methane concentrations by flame ionization detection on a Shimadzu GC-14A gas chromatograph. For each chamber run, gas sample concentrations were plotted versus sample time. Regressions with $R^2 < 0.9$ were considered non-linear and discarded; only linear (positive or negative) emission rates were used in the final analyses.

Modeling

A dynamic simulation model was developed to investigate the net exchange of carbon with the atmosphere with STELLA v. 9.1, using a time step of 0.25 years and 4th order Runge–Kutta integration.

Results

Carbon sequestration

The four tropical wetlands sequestered 42–306 g-C m^{-2} $year^{-1}$, with an average sequestration rate of 129 g-C m^{-2} $year^{-1}$ while the one natural temperate zone wetland in Ohio sequestered 143 g-C m^{-2} $year^{-1}$ (Table 1). Carbon accumulation in the two created flow-through wetlands in Ohio was considerably higher at 219 and 267 g-C m^{-2} $year^{-1}$ for the planted and unplanted wetlands respectively (Table 1), 53–87 % higher than carbon sequestration in the natural flow-through Ohio wetland.

Methane emissions

We measured methane emissions in the same seven wetlands at the six wetland sites where we estimated carbon sequestration (Table 1). Methane emissions were highest in the tropics in the isolated and floodplain wetlands in Costa Rica (220–263 g-C m^{-2} $year^{-1}$) and highest in the temperate zone in the natural Ohio wetland (57 g-C m^{-2} $year^{-1}$). Methane emission rates were lower in the flow-through tropical wetland in Costa Rica (33 g-C m^{-2} $year^{-1}$) and in the two created marshes in Ohio (average 30 g-C m^{-2} $year^{-1}$).

Previously published methane emission rates measured in the tropics/subtropics include 12–22 g-C m^{-2} $year^{-1}$ in Australian billabongs (Sorrell and Boon 1992), 3–225 g-C m^{-2} $year^{-1}$ in Louisiana freshwater marshes (Delaune and Pezeshki 2003), 30 g-C m^{-2} $year^{-1}$ in the Amazon Basin (Melack et al. 2004). In contrast, most annual flux measurements in Canadian peatlands are generally less than 7.5 g-C m^{-2} $year^{-1}$, with soil temperature, water table position, or a combination of both as primary controlling mechanisms (Moore and Roulet 1995). We show higher methane emissions in our temperate and tropical wetlands than rates published for boreal wetlands. We also showed created wetlands had methane emissions lower than or comparable to natural wetlands after 13–15 years.

Comparing carbon sequestration and methane emissions

On a carbon balance basis, our wetlands sequestered 0.3–18.2 times more CO_2 they emitted as methane (Table 1). When compared on a molecular basis, the highest ratio of carbon dioxide sequestration to methane emitted was in the planted created wetland in Ohio (50:1); the lowest ratio was 0.9:1 in the tropical floodplain site in Costa Rica. (Table 1). Most significant, six of the seven wetlands had ratios less than the global warming potential (GWP_M) of 25:1.

A wetland carbon model

A dynamic carbon model (Fig. 1) that included both soil carbon sequestration and methane emissions was developed and run for each of the seven wetlands. The model featured two carbon exchanges with the atmosphere as shown in Fig. 1—methane emissions from the wetland to the atmosphere and carbon dioxide exchange to the wetland from the atmosphere, as estimated from carbon sequestration in the soil. We did not consider volatile organic carbon (VOC) or other carbon exchanges between the wetland and the atmosphere. Model parameters include using a half-life of 7 years for methane and a GWP_{CH4} of 25.

The two-state-variable model shown in Fig. 1 is described as:

$$dM_C/dt = F_{me} - KM_C \quad (1)$$

$$dCO_{2C}/dt = KM_C - F_{CS} \quad (2)$$

where M_C is the atmospheric methane as carbon, g-C m^{-2}; CO_{2C} is the atmospheric carbon dioxide as carbon, g-C m^{-2}; F_{me} is the methane emissions from wetland as carbon, g-C m^{-2} $year^{-1}$; F_{cs} is the carbon dioxide exchange from the atmosphere as carbon, g-C m^{-2} $year^{-1}$; k is the first-order decay of methane in the atmosphere, $year^{-1}$ (initial model assumption of 7-year half-life).

We then defined the carbon dioxide equivalent (CO_{2eq}) as:

$$CO_{2eq} = CO_2 + (GWP_M \times M_{CH_4}) \quad (3)$$

where CO_2 is the atmospheric carbon dioxide, g-CO_2 m^{-2}; M_{CH4} is the atmospheric methane, g-CH_4 m^{-2}; GWP_M is 25.

Our model simulated a theoretical 1-m^{-2} atmosphere column over a 1-m^2 wetland plot. F_{cs} for our initial simulations was estimated from soil carbon sequestration measurements described above, corrected for methane emissions. Methane's lifetime in

Table 1 Comparison of carbon sequestration and methane emissions on atmospheric gases in 7 wetlands at 6 sites in Ohio, Costa Rica, and Botswana, including ratios of sequestration:methane emissions in terms of carbon and CO_2/CH_4 at the start and after 100 years of model simulation

Climate	Humid temperate			Humid tropical		Dry tropical	
Wetland type	Created flow-through wetlands		Natural flow-through wetland	Natural flow-through wetland	Natural isolated wetland	Natural floodplain	Natural inland delta
Wetland name	Olentangy River Wetlands, Ohio[a]		Old Woman Creek, Ohio	Earth University, Costa Rica	La Selva, Costa Rica	Palo Verde, Costa Rica	Okavango, Botswana
F_{cs}, Carbon sequestration, g-C m^{-2} $year^{-1}$	−243 (overall)		−143	−306	−84	−84	−42
	−219 (Wetland 1)	−267 (Wetland 2)					
F_{me}, Methane emissions, g-C m^{-2} $year^{-1}$	+30 ± 14 (122) overall		+57 ± 18 (61)	+33 ± 5 (75)	+220 ± 64 (66)	+263 ± 64 (75)	+72 ± 8 (26)
	+12 ± 4 (55) (Wetland 1)	+47 ± 23 (67) (Wetland 2)					
Net carbon exchange with atmosphere, g-C m^{-2} $year^{-1}$	−213 (overall)		−86	−273	+136	+179	+30
	−207 (Wetland 1)	−220 (Wetland 2)					
F_{cs}/F_{me}	8.1:1		2.5:1	9.3:1	0.3:1	0.3:1	0.6:1
Carbon dioxide sequestration, g-CO_2 m^{-2} $year^{-1}$	−891 (overall)		−524	−1122	−308	−308	−154
	−803 (Wetland 1)	−979 (Wetland 2)					
Methane emissions, g-CH_4 m^{-2} $year^{-1}$	40 ± 18 (overall)		+76 ± 24	+44 ± 6	+293 ± 86	+350 ± 86	+96 ± 11
	16 ± 5 (Wetland 1)	63 ± 31 (Wetland 2)					
$CO_2:CH_4$ ratio	22.3:1 (overall)		7:1	25:1	1.1:1	0.9:1	1.6:1
	50.2:1 (Wetland 1)	15.5:1 (Wetland 2)					
$CO_2:CH_4$ ratio, 100-year simulation	223:1 (overall)		71:1	255:1	13.1:1	11:5	18.6:1
	500:1 (Wetland 1)	157:1 (Wetland 2)					
Sink, year	0 (overall)		31	0	214	255	140
	0 (Wetland 1)	8 (Wetland 2)					

The year at which the wetland goes from being a net radiative force to a net radiative sink is also indicated for each wetland. Negative signs indicate carbon fluxes out of the wetlands; positive signs indicate carbon fluxes into the wetlands

Signs on fluxes are relative to atmosphere. minus sign (−) indicates decrease in atmosphere; positive sign (+) indicates increase in atmosphere

[a] For Olentangy River Wetlands in Ohio, Wetland 1 refers to a planted created wetland while Wetland 2 was a naturally colonizing created wetland. See Mitsch et al. 2012) for details

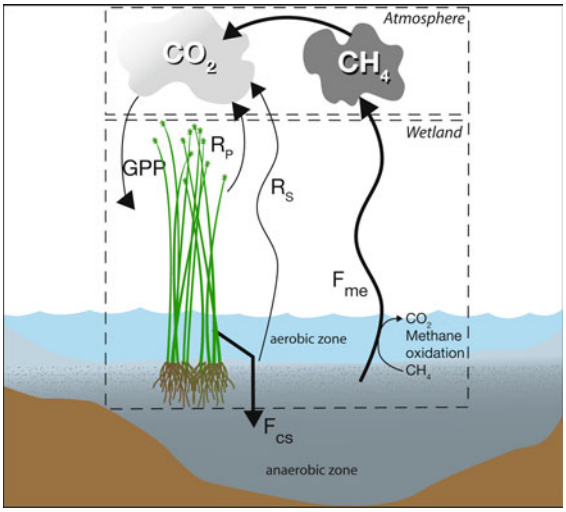

Fig. 1 Conceptual model of carbon budget in a wetland and its carbon exchanges with the atmosphere. F_{cs} carbon sequestration; F_{me} methane emissions; *GPP* gross primary productivity; R_P plant respiration; R_S soil respiration. The conceptual model was translated to a STELA simulation model that was designed to run over tens to hundreds of years

the atmosphere has been reported as 8–10 years before being oxidized to CO_2 (Fuglestvedt et al. 2003; Schmidt 2004) but we used a 7-year half-life and a first-order decay that is also reported in the literature. Using this less rapid decay of methane in the atmosphere is a conservative assumption that prevents us from overstating the net benefit of wetlands in the carbon cycle.

When this model is simulated for the seven wetlands described above, each has a ratio of carbon dioxide decrease to methane increase well above the GWP_M of 25:1 within 300 years (Fig. 2). For the tropical flow-through slough, 255 kg of CO_2 are taken out of the atmosphere for every kg of CH_4 increase in the atmosphere after 100 years. For the created temperate zone wetlands averaged together, the ratio is 223 kg of CO_2 for every kg of CH_4 increase. For these 3 wetland simulations, the net CO_2 becomes negative almost immediately (i.e., the wetlands become sinks of greenhouse gases almost from the start). The natural temperate wetland, with a ratio of 71:1 after 100 years, becomes a sink after 31 simulated years. The three remaining tropical wetlands become sinks after 140–255 simulated years (Table 1).

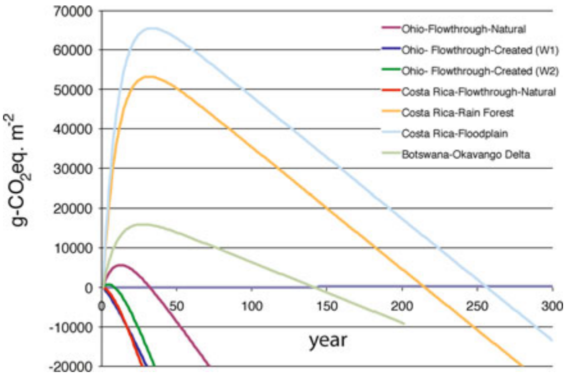

Fig. 2 Three-hundred year simulations of our atmospheric carbon budget model for the seven temperate and tropical wetlands from Ohio, Costa Rica, and Botswana described in this paper. The simulated amount, called CO_2-equivalent, is carbon dioxide plus 25 times methane. All wetlands eventually cause net decrease in CO_2-equivalent in the atmosphere (below the zero line) and several of the wetlands are net sinks from the start

Discussion

Carbon sequestration

Our temperate and tropical wetlands soil sequestration rates are generally 4 to 5 times greater than those estimated for boreal wetlands (Table 2). Gorham (1991) estimated an overall rate of 29 g-C m^{-2} $year^{-1}$ for North American peatlands while Turunen et al. (2002) described a carbon sequestration range of 15–26 g-C m^{-2} $year^{-1}$ for boreal peatlands. Several studies in temperate and tropical regions provide rates similar to ours. Carbon accumulation in the Florida Everglades was estimated by Reddy et al. (1993) as 86–387 g-C m^{-2} $year^{-1}$ with highest rates in areas of high phosphorus loadings. Carbon accumulation was estimated at 480 g-C m^{-2} $year^{-1}$ for a highly productive *Cyperus papyrus* wetland in Uganda (Saunders et al. 2007), but only 94 g-C m^{-2} $year^{-1}$ for the past 500 years in the upper meter of a core from Indonesia (Page et al. 2004).

Methane emissions

Previously published methane emission rates (Table 3) measured in the tropics/subtropics include 12–22 g-C m^{-2} $year^{-1}$ in Australian billabongs (Sorrell and Boon 1992), 3–225 g-C m^{-2} $year^{-1}$ in Louisiana freshwater marshes (Delaune and Pezeshki 2003), 30 g-C m^{-2} $year^{-1}$ in the Amazon Basin

Table 2 Comparison of carbon sequestration in wetlands in the literature with rates reported in this study

Wetland type	g-C m^{-2} $year^{-1}$	Reference
General range for wetlands	20–140	Mitra et al. (2005)
Northern peatlands		
Peatlands (North America)	2	Gorham (1991)
Boreal peatlands	15–26	Turunen et al. (2002)
Temperate peatlands	10–46	Turunen et al. (2002)
Temperate/Tropical Wetlands		
Coastal wetlands, North America		Chmura et al. (2003)
Mangroves	180	
Salt marshes	220	
Coastal wetlands, North America		Craft (2007); Craft et al. (2009)
Tidal freshwater wetlands	140 ± 20	
Brackish marshes	240 ± 30	
Salt marshes	190 ± 40	
Mangrove swamps, S.E. Asia	90–230	Suratman (2008)
Coastal wetlands, S.E. Australia		Howe et al. (2009)
Undisturbed sites	105–137	
Disturbed sites	64–89	
Tropical freshwater wetland	56 (for 24,000 years) 94 (for last 500 years)	Page et al. (2004)
Cyperus wetland in Uganda	480	Saunders et al. (2007)
Prairie pothole wetlands, North America		Euliss et al. (2006)
Restored (semi-permanently flooded)	305	
Reference wetlands	83	
Florida Everglades	86–387	Reddy et al. (1993)
This study		
Temperate flow-through wetlands, Ohio	124–160	This study
Created temperate marshes, 10-years old, Ohio	181–193	Anderson and Mitsch (2006)
Created temperate marshes, 15-years old, Ohio	219–267	This study
Tropical flow-through wetland, Costa Rica	306	This study
Tropical forest wetland, Costa Rica	84	This study
Tropical floodplain wetland, Cost Rica	84	This study
Tropical seasonally flooded wetland, Botswana	42	This study

(Melack et al. 2004). In contrast, most annual flux measurements in Canadian peatlands are generally less than 7.5 g-C m^{-2} $year^{-1}$, with soil temperature, water table position, or a combination of both as primary controlling mechanisms (Moore and Roulet 1995). We show higher methane emissions in our temperate and tropical wetlands than rates published for boreal wetlands. We also showed created wetlands had methane emissions lower than or comparable to natural wetlands after 13–15 years.

Additional wetland comparison

We used our model to compare carbon sequestration (F_{cs}) and methane emissions (F_{me}) for 14 additional wetlands from around the world where both carbon sequestration and methane emissions were measured at the same site by other researchers (Brix et al. 2001; Whiting and Chanton 2001; Heikkinen et al. 2002; Hendriks et al. 2007). These fluxes and model results are compared with our original seven wetlands in

Table 3 Comparison of methane emissions (as carbon) from wetlands in the literature with rates reported in this study

Wetland type	g-C m^{-2} year^{-1}	Reference
Northern Peatlands		
Canadian peatlands	<7.5	Moore and Roulet (1995)
Temperate/Tropical Wetlands		
Amazon basin, Brazil	40–215	Devol et al. (1988)
Australian billabong	12–22	Sorrell and Boon (1992)
Louisiana freshwater marshes	3–225	Delaune and Pezeshki (2003)
Louisiana bottomland hardwood forest	10	Yu et al. (2008)
Amazon Basin	30	Melack et al. (2004)
Spring-fed wetlands, Mississippi	51	Koh et al. (2009)
Freshwater marsh, Virginia	62	Whiting and Chanton (2001)
Temperate forested wetlands	35	Bartlett and Harriss (1993)
Orinoco floodplain, Veneuzela	9	Smith et al. (2000)
This study		
Temperate flow-through wetlands, Ohio	57 ± 18	Nahlik and Mitsch (2010)
Created temperate marshes, Ohio	30 ± 14	Nahlik and Mitsch (2010)
Tropical flow-through wetland, Costa Rica	33 ± 5	Nahlik and Mitsch (2011)
Tropical floodplain wetland, Costa Rica	263 ± 64	Nahlik and Mitsch (2011)
Tropical rain forest isolated wetland, Costa Rica	220 ± 64	Nahlik and Mitsch (2011)
Tropical seasonally flooded wetland, Botswana	72 ± 8	This study

Table 4. Although these studies used different methods to measure carbon sequestration and methane emissions than we did in our seven wetlands, their estimates of carbon sequestration and methane emissions are reasonable and within ranges expected for these types of wetlands.

Carbon sequestration values in the additional 14 studies ranged from −8 g-C m^{-2} year^{-1} (net emissions in an ombrotrophic peatland in the Russian tundra; Heikkinen et al. 2002) to 552 g-C m^{-2} year^{-1} in a *Phragmites* marsh in Denmark (Brix et al. 2001). Methane emissions ranged from 1.2 g-C m^{-2} year^{-1} in a Russian tundra peatland to 132 g-C m^{-2} year^{-1} in a Virginia *Peltandra* marsh. Overall, for the 21 wetlands described in this study, carbon sequestration averaged 214 ± 66 (6) in the tropical wetlands, 320 ± 51 (7) for the temperate wetlands, and 49 ± 18 (8) for the boreal wetlands.

From the 21 wetlands listed in Table 4, tropical/subtropical wetland ($n = 6$) methane emissions averaged 119 ± 40 g-C m^{-2} year^{-1} while temperate wetlands averaged 58 ± 15 ($n = 7$). By contrast, the annual methane flux from the 8 boreal wetland sites (54–67°N) in Table 4 (19 ± 7 g-C m^{-2} year^{-1}) averaged one-sixth to one-third of the tropical and temperate emissions, respectively.

The initial ratios of carbon dioxide sequestration to methane emissions for the 21 wetlands range from −18:1 to 57:1, with each extreme in the boreal peatlands (Table 4). Initially only five of the 21 wetlands had ratios above the 25:1 GWP ratio before simulations. Ratios were <25:1 for the other 16 wetlands; these wetlands would thus be judged by some as net sources of radiative forcing.

We ran our model for the 14 additional wetlands. All except two—the Russian peatlands that had negative carbon sequestration to begin with—became net sinks of carbon, with ratios well above 25:1 well within 100 years (Table 4). The two Russian peatlands could not mathematically become sinks, as data from both showed net CO_2 release rather than CO_2 sequestration.

Table 4 Carbon dioxide sequestration: methane emission ratios from 21 tropical/subtropical, temperate and boreal freshwater wetlands where both measurements were taken

Location	Wetland type	Sequestration (gCO_2 m^{-2} $year^{-1}$)	Methane emission (gCH_4 m^{-2} $year^{-1}$)	CO_2:CH_4	Reference	ΔCO_2: ΔCH_4, 100-year simulation	Net CO_2 sink, year	Net Annual Carbon retention, g-C m^{-2} $year^{-1}$
Tropical/subtropical								
Earth University, Costa Rica	**Flow-through forested tropical slough**	**1,122**	**44**	**25.5:1**	**This study**	**255:1**	**0**	**306**
LaSelva, Costa Rica	Isolated wetland in tropical rain forest	308	293	1.1:1	This study	13.1:1	214	84
Palo Verde, Costa Rica	Riverine coastal floodplain	308	350	0.9:1	This study	11:5:1	255	84
Okavango Delta, Botswana	Inland freshwater delta	154	96	1.6:1	This study	18.6:1	140	42
Florida	*Typha* marsh	1,304	68.8	19.0:1	Whiting and Chanton (2001)	163:1	7	309
Florida	*Typha* marsh	1,518	96	15.8:1	Whiting and Chanton (2001)	132:1	12	342
Temperate								
Old Woman Creek, Lake Erie, OH	Flow-through *Nelumbo/ Phragmites* marsh	524	76	6.9:1	This study	71:1	31	143
Olentangy River Wetlands, OH	**Created flow-through *Sparganium/ Typha/Scirpus* marsh**	**803**	**16**	**50.2:1**	**This study**	**500:1**	**0**	**219**
Olentangy River Wetlands, OH	Created flow-through *Typha/ Leersia* marsh	979	63	15.5:1	This study	157:1	8	267
Horstermeer polder, The Netherlands	**Formerly farmed peatland**	1,140	42	**27.4:1**	**Hendriks et al.** (2007)	**249:1**	**0**	**280**
Denmark	***Phragmites* marsh**	2,024	64	**31.6:1**	**Brix et al.** (2001)	**289:1**	**0**	**504**
Virginia	*Typha* marsh	1,195	108.8	11.0:1	Whiting and Chanton (2001)	84:1	25	244
Virginia	*Peltandra* marsh	1,544	176	8.8:1	Whiting and Chanton (2001)	62:1	36	289
Boreal								
Alberta Canada	*Carex* fen	552	73.6	7.5:1	Whiting and Chanton (2001)	50:1	46	96
Alberta Canada	*Carex* fen	179	35.2	5.1:1	Whiting and Chanton (2001)	26:1	95	23

Table 4 continued

Location	Wetland type	Sequestration (gCO_2 m^{-2} $year^{-1}$)	Methane emission (gCH_4 m^{-2} $year^{-1}$)	CO_2:CH_4	Reference	ΔCO_2: ΔCH_4, 100-year simulation	Net CO_2 sink, year	Net Annual Carbon retention, g-C m^{-2} $year^{-1}$
Alberta Canada	*Carex* fen	365	59.2	6.2:1	Whiting and Chanton (2001)	36:1	66	55
Russian tundra	*Peatland flarks-water table*	−22	16	*−1.4:1*	*Heikkinen et al.* (2002)	*	–	*−6**
Russian tundra	Peatland-intermediate flarks	139	8	17.4:1	Heikkinen et al. (2002)	148:1	9	32
Russian tundra	Peatland- wet lawn	128	6	22.4:1	Heikkinen et al. (2002)	197:1	3	31
Russian tundra	**Peatland-intermediate lawns**	92	2	**57.3:1**	**Heikkinen et al.** (2002)	**543:1**	**0**	**24**
Russian tundra	*Ombrotrophic peatland*	−29	2	*−18.3:1*	*Heikkinen et al.* (2002)	*	–	*−1.2**

Model results after 100 simulated years for the wetlands including ratio of change in atmospheric CO_2/change in atmospheric CH_4 and the year in which the wetland becomes carbon neutral. Net annual carbon retention of each wetland is also indicated. Negative numbers indicates net release of CO_2 from the beginning

* Net CO_2 release

Bold indicates wetlands that were carbon neutral or better at year 0 of simulation

Italics indicates wetlands that cannot become carbon sinks because they were initially CO_2 sources

Methane decay

Our model simulated a 7-year half-life for methane—a slow degradation of methane given that an 8–10 year "lifetime" is often reported. We reran the models using a higher sometimes-quoted value of 12-year half-life for methane (IPCC 2007) and still found similar results, with all of the wetlands except the two that are CO_2 sources to begin with becoming sinks. For both sets of half-life simulations, net carbon dioxide equivalent retention as shown in Table 4 is similar after 100 years.

A comparison of wetland types for carbon sequestration

Overall four of the five most effective wetlands in net retention of carbon were in the temperate zone. In our study of seven wetlands, the two created freshwater marshes in Ohio and the flow-through tropical slough in Costa Rica were the most effective for net carbon retention. The created wetlands sequestered more carbon and emitted less methane than did the reference wetland in Ohio at Old Woman Creek. The flow-through tropical slough in humid tropical Costa Rica was similar in geomorphology and hydrology to these wetlands and also had a high net carbon retention. It could be that the flow-through conditions optimize carbon sequestration while keeping methane emissions low in all of these wetlands. From the 14 additional studies that we investigated, the most effective wetlands for net carbon retention were in Europe: a formerly farmed peatland in the Netherlands and a *Phragmites* marsh in Denmark. The Dutch peatland was an abandoned peat meadow that had been returned to a wetland nature reserve 10 years prior to their study (Hendriks et al. 2007). Because of relatively low methane emissions (31 g-C m^{-2} $year^{-1}$) in a relatively high productivity meadow (gross primary productivity = 1,177 g-C m^{-2} $year^{-1}$), the site has a CO_2 sequestered/CH_4 emission ratio of 27.4:1 at time zero and 249:1 ratio at the end of the 100-year simulation. The *Phragmites* marsh in Denmark (Brix et al. 2001) has an even higher ratio of 289:1 after 100 years. Overall, the Netherlands and Danish wetlands had a net accumulation of 280 and 504 g-C m^{-2} $year^{-1}$, respectively. For comparison Mander et al. (2008) found 656 g-C m^{-2} $year^{-1}$ of carbon sequestration in constructed wastewater wetlands with low methane emissions.

Net carbon sequestration rates in boreal peatlands are low, averaging 29 g-C m^{-2} $year^{-1}$ at our 8 boreal sites (Table 5). Bridgham et al. (2006) suggested an average of 23 g-C m^{-2} $year^{-1}$ for North America–mostly Canadian and Alaskan peatlands. Net carbon accumulation rates are much higher in temperate and tropical regions, averaging 278 and 194 g-C m^{-2} $year^{-1}$ respectively (Table 5), averaging 10–7 times the rates we found for boreal sites.

Methane emissions from the world's wetlands

Comparison of methane emission measurements here suggests that tropical/subtropical wetlands may have higher methane emission rates than previously reported, as suggested by Bloom et al. (2010). Overall, methane emissions from our 21 sites, distributed over the three climatic zones in Table 5, yield a net emission of methane of 448 Tg/year (as C) from the world's wetlands, with 78 % coming from the tropics/subtropics. Our estimate of the world's wetland methane emissions is twice the 227 Tg/year of methane emissions from the world's wetlands estimated by Bloom et al. (2010).

Table 5 World's wetland net carbon retention estimated from 21 wetland simulations described in this paper and listed in Table 4

	Tropical/sub-tropical wetlands	Temperate wetlands	Boreal peatlands	Total or weighted average
Net carbon retention, g-C m^{-2} $year^{-1}$ (ave ± std error (# wetlands))	194 ± 56 (6)	278 ± 42 (7)	29 ± 13 (8)	118 (21)
Area of wetlands, $\times 10^6$ km^2	2.9	0.6	3.5	7.0
Total carbon retention, $\times 10^{15}$ g-C $year^{-1}$	0.56	0.16	0.11	0.83

Area of wetlands for each region is from Lehner and Döll (2004) and Mitsch and Gosselink (2007). Seven million square kilometers is a conservative (low) estimate of the extent of the world's wetlands

Wetlands as global carbon sinks

Using a conservative estimate of 7 million km^2 of wetlands in the world (5–6 % of the landscape; Mitsch and Gosselink 2007; Mitsch et al. 2010), the distribution of wetlands in these three general climatic zones as described by Lehner and Döll (2004), and our net carbon retention values in Table 4, we estimate that the world's wetlands serve as net sinks of 0.83 Pg/year or 830 Tg/year (Table 5). Overall, this number results from approximately 1,280 Tg-C/year of carbon dioxide sequestered from the atmosphere and about 448 Tg-C/year returned to the atmosphere as methane emissions. The weighted average of carbon sequestration in the world's wetlands is 118 g-C m^{-2} year^{-1}.

This net accumulation rate is 12 % of the estimated 7.0 Pg/year from fossil fuel combustion, is mid-range of the 0.4–1.2 Pg/year estimated for soil sequestration from the entire terrestrial landscape, is about 75 % of the estimated retention of carbon by the world's oceans, and is 4 times the total terrestrial carbon sinks reported for China (Piao et al. 2009). More measurements of wetland carbon sequestration are needed to refine this number, particularly in the tropics, but if accurate, wetland net sequestration of 12 % of anthropogenic carbon emissions may be the lost carbon sink as described by Lenhart (2009).

Conclusions

We have shown here that

1. Most wetlands are net carbon sinks and not radiative sources of climate change, even when methane emissions are considered, when taking into account the decay of methane in the atmosphere.
2. The world's wetlands are significant sinks of carbon on the order of 830 Tg/year, equaling or surpassing previous estimations.
3. Because wetlands provide many ecosystem services in addition to carbon sequestration, it is shortsighted to suggest that wetlands should not be created or restored because of GHG emissions. If we consider the savings that wetlands give us from fossil fuel consumption for the ecosystem services of water quality improvement, flood mitigation, and coastal and storm protection (for coastal wetlands), their service as carbon sinks is even more impressive that without considering these savings.

Acknowledgments This research was partially supported by U.S. Environmental Protection Agency grants EM-83329801-0 and MX95413108-0 the U.S. Department of Energy Grant DE-FG02-04ER63834 and National Science Foundation Grants CBET-1033451 and CBET-0829026. We thank A. Altor, B. Kohlmann, C. Hernandez, J. Yeomans and many researchers and students at the Olentangy River Wetlands for assistance in field research. Ü. Mander was supported with a Fulbright fellowship as a visiting scientist to the Olentangy River Wetland Research Park. A. Mischo kindly assisted with the illustrations. Olentangy River Wetland Research Park Publication 2012-0xx.

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