

Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration

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ABSTRACT

Carbon fixation under wetland anaerobic soil conditions provides unique conditions for long-term storage of carbon into histosols. However, this carbon sequestration process is intimately linked to methane emission from wetlands. The potential contribution of this emitted methane to the greenhouse effect can be mitigated by the removal of atmospheric CO₂ and storage into peat. The balance of CH₄ and CO₂ exchange can provide an index of a wetland's greenhouse gas (carbon) contribution to the atmosphere. Here, we relate the atmospheric global warming potential of methane (GWP_M) with annual methane emission/carbon dioxide exchange ratio of wetlands ranging from the boreal zone to the near-subtropics. This relationship permits one to determine the greenhouse carbon balance of wetlands by their contribution to or attenuation of the greenhouse effect via CH₄ emission or CO₂ sink, respectively. We report annual measurements of the relationship between methane emission and net carbon fixation in three wetland ecosystems. The ratio of methane released to annual net carbon fixed varies from 0.05 to 0.20 on a molar basis. Although these wetlands function as a sink for CO₂, the 21.8-fold greater infrared absorptivity of CH₄ relative to CO₂ (GWP_M) over a relatively short time horizon (20 years) would indicate that the release of methane still contributes to the overall greenhouse effect. As GWP_M decreases over longer time horizons (100 years), our analyses suggest that the subtropical and temperate wetlands attenuate global warming, and northern wetlands may be perched on the "greenhouse compensation" point. Considering a 500-year time horizon, these wetlands can be regarded as sinks for greenhouse gas warming potential, and thus attenuate the greenhouse warming of the atmosphere.

1. Introduction

Wetlands occupy only a small portion of the earth's land surface (2% to 6%; Aselmann and Crutzen, 1989; Mitsch and Gosselink, 1993; Buringh, 1984) yet contain a large portion of the carbon stored in the terrestrial soil reservoir

($\sim 1500 \times 10^{15}$ gC; Schlesinger, 1991). Estimates for carbon storage in histosols as a per cent of the total soil organic carbon reservoir range from 3 to 68% (Buringh, 1984; Schlesinger, 1991; Bolin et al., 1977; Post et al., 1982). The combination of elevated water tables, high productivity and lower decomposition has led to significant carbon storage in these soil types, especially in high latitude wetlands (Gorham, 1991). In flooded soils, CO₂ fixation by vegetation can offset decomposition resulting in net carbon accumulation in the soil. The unique reduced environment of wetland soils facilitates long-term storage of carbon in these systems due to slow diffusion of oxygen into these

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soils (1000 times more slowly in water saturated soils than in dry soils). Carbon accumulation is also favored at low temperatures, which is evident by a majority of the world's peat deposits being located within higher latitudes (Gorham, 1981; Schlesinger, 1984). However, peat accumulation can also occur in tropical regions with measured peat accumulations rates of 0.25 to 1.1 cm/yr in the subtropical Everglades of Florida (Reddy et al., 1993).

Prior to the industrial era, wetlands were the main source of atmospheric methane (CH_4) with other relatively minor contributors (Chappellaz et al., 1993). As carbon cycles through a wetland, a portion is lost (mineralized) to gaseous end products such as methane. Carbon fixation (primary production) in flooded wetlands is strongly coupled to CH_4 production and emission to the atmosphere (Whiting and Chanton, 1993). The amount of CO_2 exchanged on a daily basis is positively correlated to CH_4 emitted across wetlands ranging from the subarctic to the subtropics, with CH_4 emission representing roughly 3% of the net daily ecosystem uptake of CO_2 on a molar basis (Whiting and Chanton, 1993). The quantity of CH_4 contained belowground and emitted is closely associated with the standing biomass and activity of the primary producers within a number of these systems (Chanton et al., 1993; Whiting and Chanton, 1992; Whiting et al., 1991). Results from the extensive peatlands of Hudson Bay lowlands also indicate the importance of primary productivity in controlling CH_4 emissions (Klinger et al., 1994). This process is also influenced by the system's hydrologic regime (Moore et al., 1990; Bubier et al., 1993; Roulet et al., 1993; Romanowicz et al., 1995). Radiocarbon evidence from belowground and emitted CH_4 from northern Minnesota peatlands suggests that methanogenesis is strongly linked to living vegetation and hydrology (Chanton et al., 1995).

2. Wetlands and greenhouse gas exchange

Wetlands may be considered a greenhouse gas sink as CO_2 is removed from the atmosphere and stored in the soil carbon pool. However, a wetland acts as a greenhouse gas source when it emits CH_4 to the atmosphere which contributes to the atmospheric absorption of infrared radiation. Given

that flooded wetlands generally function to sequester CO_2 from and release CH_4 to the atmosphere, a combination of two factors determines whether these offsetting processes make a wetland system an overall contributor to the greenhouse effect. The first factor, the ratio of CH_4 emission to CO_2 uptake (mole/mole) for the ecosystem, provides an index of the ecosystem's greenhouse gas (carbon) exchange balance with the atmosphere (Gorham, 1991; Rodhe et al., 1991). The second factor compares the relative potential of greenhouse gases to absorb infrared radiation in the atmosphere, an index termed global warming potential (GWP; Rogers and Stephens, 1988; Rodhe, 1990; Lashof and Ahuja, 1990). The instantaneous infrared absorption of CH_4 is 25 times greater than that of CO_2 (mole to mole; Rodhe, 1990; Lashof and Ahuja, 1990; Lelieveld et al., 1993; IPCC, 1996). The GWP index was developed to integrate over time the climatic forcing of a particular gas (e.g., CH_4) relative to the greenhouse effect of CO_2 . The GWP index incorporates direct radiative effects, the lifetime of the gases in the atmosphere, and indirect effects caused by chemical feedbacks (Rodhe et al., 1991; Lelieveld et al., 1993; IPCC, 1996).

The GWP of methane (GWP_M) is dependent on the time interval over which the radiative forcing is integrated. Over a short-term integration period (ca. 20 years), the GWP_M is estimated to be 21.8 (mole CH_4 /mole CO_2 ; Lelieveld et al., 1993). However, the GWP_M falls to between 7.6 and 2.6 when considered over the time horizons of 100 to 500 years (Fig. 1) as proposed by IPCC (1996). This reduction of GWP is due primarily to the extended lifetime of CO_2 in the atmosphere relative to CH_4 (Lelieveld et al., 1993, 1998; IPCC, 1996). Whether a wetland functions as a net greenhouse source or sink depends on the difference between the greenhouse "equivalents" (total infrared absorption potential; Rudd et al., 1993) of CO_2 taken up and the greenhouse "equivalents" of methane released.

To illustrate how wetlands function as a source or sink of greenhouse gas equivalents, we relate the two factors, the ratio of CH_4 emission to CO_2 uptake (CH_4/CO_2) with GWP_M , in a simple model (Fig. 2). A wetland system reaches a greenhouse gas balance (or *greenhouse compensation*) when its CO_2 uptake and CH_4 release are equal in greenhouse gas equivalents (dashed line, Fig. 2).

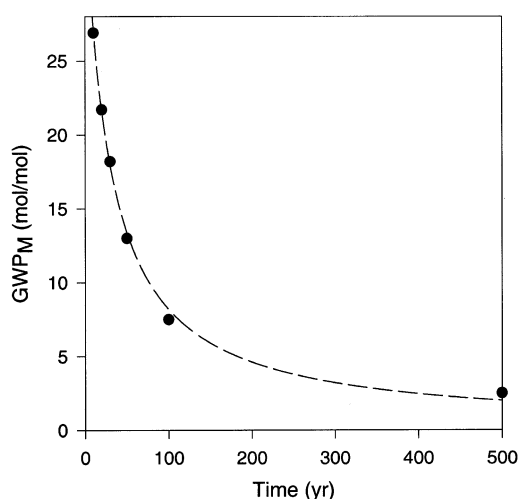


Fig. 1. Relationship between integration time and the global warming potential of methane (GWP_M) adapted from Lelieveld et al., 1993, 1998 (solid points) based on the IPCC-B increasing emission scenario (IPCC, 1996). The dashed line is an empirical best fit of $y^{-1} = a + bx$; where $y = GWP_M$, $x = \text{time (years)}$; $R^2 = 0.998$.

The greenhouse compensation point is dependent on both the CH_4/CO_2 emission-exchange ratio and the time-dependent GWP_M . We have expressed this CH_4/CO_2 and GWP_M relationship over the range of 26 to 2.5 GWP_M , which encompasses an integration time between zero and 500 years (Fig. 1). As time increases (and GWP_M decreases), the 100-year time-horizon approaches the lifetime of CO_2 in the atmosphere and the time for successional steady-state to occur in many terrestrial ecosystems (Crocker and Major, 1955; Olson, 1957; Odum, 1969). The upper time horizon (500-year) approaches climate change effects associated with global ocean circulations (Lelieveld et al., 1998). A wetland system acts as a greenhouse sink when the removal of greenhouse equivalents via CO_2 uptake is greater than the release of greenhouse equivalents associated with CH_4 emission (Fig. 2, *SINK* region). Considering a short-term horizon, a relatively low CH_4/CO_2 exchange ratio can facilitate this sink. Over longer time horizons and correspondingly lower GWP_M , a wetland could still be considered a greenhouse sink even with an elevated CH_4/CO_2 ratio. A wetland is a greenhouse source when the $CH_4/$

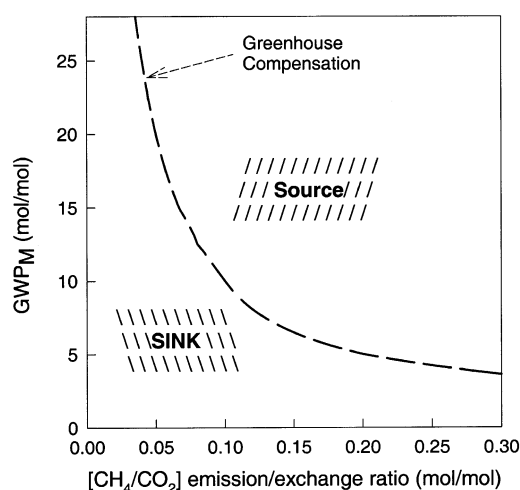


Fig. 2. A model of the relationship between the greenhouse warming potential of methane (GWP_M), expressed as CO_2 equivalents, and the molar ratio of CH_4 emitted to CO_2 taken up (CH_4/CO_2) by a wetland. The GWP_M range encompasses the same time horizon as in Fig. 1. The dashed line is the greenhouse compensation boundary where the greenhouse potential uptake of CO_2 is offset by the emission of CH_4 [$GWP_M \cdot (CH_4/CO_2) = 1$]. In the *SINK* region, the wetland system acts as a net greenhouse sink where the removal of global warming equivalents via CO_2 uptake is greater than the release of global warming equivalents via CH_4 emission. A wetland acts as a greenhouse source (*Source* region) when either GWP_M is high or the CH_4/CO_2 ratio is large.

CO_2 ratio is elevated and GWP_M is considered over a short time horizon (Fig. 2, *Source* region).

The previously reported 3% CH_4/CO_2 relationship was measured primarily during the seasonal peak of net daily ecosystem production and methane emission (Whiting and Chanton, 1993). However, an annual exchange of gases is necessary in order to estimate an ecosystem's contribution to net atmospheric radiative forcing. Annual exchange rates integrate the seasonal exchange of CO_2 and emission of CH_4 over the development and senescence of plant communities, which provide substrates for methanogens and conduits for methane emission to the atmosphere (Chanton and Dacey, 1991). We report here the results of measurements located within wetlands extending from the subtropics of Florida, USA, a temperate marsh of Virginia, USA, to the boreal forest of Alberta,

Canada and relate these annual exchanges to the model presented.

3. Methods

We conducted seasonal measurements of CH₄ and CO₂ gas exchange within three wetlands that range from a near-subtropical *Typha latifolia* (number plots measured, $n = 2$) stand in Florida (30° 30' N, 84° 15' W), a mid-latitude temperate marsh in Virginia (37° N, 76° 30' W) with *Typha latifolia* ($n = 4$) and *Peltandra virginica* ($n = 3$) vegetation, and a boreal fen dominated by *Carex* ($n = 6$) in Alberta, Canada (54° N, 113° W). Water levels were 5 to 20 cm above the soil surface in the temperate wetlands over an annual period, while the boreal fen had water levels ranging from 20 cm above to 9 cm below the peat surface over the 6-month thaw period between May and October.

At each site we installed aluminum frames (collars, 0.43 m²) into the soil. Collar sides extended approximately 10 to 15 cm into the sediment with the flat top of the collar normally just below or at the water surface. This provided a solid base of support for the gas exchange chambers with minimal disturbance to the vegetation and sediments throughout annual sampling.

We utilized portable, climate-controlled, instrumented phyt chambers to control chamber air temperature and CO₂ and to capture gas for CH₄ emission measurements. It is a closed-system design made up of three major parts: a clear chamber with aluminum framing, a climate control system, and a sensor array (Whiting et al., 1992; Chanton and Whiting, 1995). The sensors measure chamber air temperature, relative humidity, incident light (PAR), and CO₂ concentrations utilizing a LI-COR Model 6200 Portable Photosynthesis System (LI-COR, Inc., Lincoln, Nebraska, USA). The chambers are adjustable in height, covering 0.43 m² of surface area, and range in volume from 280 to 1000 liters. Three sides and the top are covered with transparent (~90% PAR transmission) Teflon film, with the remaining side composed of a clear polycarbonate sheet. The chamber is placed on top of the collar during sampling and sealed with closed-cell foam gasket and clamps. The chamber, used for the *P. virginica* site, covered 1 m² (800 liters in volume) and is not deployed on

collars but is equipped to float over the plants. Chamber air temperature was regulated within 1°C of outside temperature by controlling the flow of cold water pumped from an ice-water reservoir through a heat exchanger attached to the inside wall of the polycarbonate side. Chamber air was blown through the heat exchange coils with brushless box fans with additional fans circulating chamber headspace at velocities normally encountered by plants at the top of the canopy (<1 m/s).

Methane concentrations of gas samples were determined utilizing a FID gas chromatograph with a 6-port gas sampling valve (1 ml loop) attached. Samples were analyzed within a few hours of collection. Scott standard gases (Scott Specialty Gases, Inc. Plumsteadville, PA, USA) were used to calibrate the GC for CH₄ and the LICOR for CO₂.

Chambers were typically deployed between 0900 and 1600 LT to utilize maximum light levels to define CO₂ exchange and light response curves. To obtain an estimate of daily exchange of CO₂, chambers were also covered by a blackout cloth and chamber temperature varied to simulate nighttime respiration conditions. CO₂ exchange was integrated over a 24-h period using both light levels and temperature as environmental drivers. Further details of the chamber system and technique are described in Whiting et al. (1991).

In the Florida site, measurements of CH₄ emission and CO₂ exchange were made on a monthly basis for 2 years. The Virginia temperate marsh was sampled on a monthly schedule during the growing season and bimonthly during the period of plant senescence over a 2-year period. The boreal fen site was sampled every 2 weeks from the May thaw until a late October freeze over a 3-year period. Additional measurements were conducted in the boreal site during March to characterize winter emissions. CH₄ emission and CO₂ exchange rates were integrated over annual periods (Table 1).

4. Results and discussion

Net carbon dioxide uptake and methane emission were exhibited at all sites integrated over an annual period (Table 1). All wetlands were a sink for carbon dioxide over the measured annual periods. The southern marshes have 3 to 4×

Table 1. Annual exchange of CH_4 and CO_2 in several wetlands ranging from the near-subtropics to the boreal plain

Site	Date	CH_4 (mole m^{-2} yr^{-1})	CO_2	CH_4/CO_2 (mole/mole)	Compensation point (GWP_{Mcp})
Florida <i>Typha</i>	1992	4.3	81.5	0.05	18.9
Florida <i>Typha</i>	1993	6.0	94.9	0.06	15.9
Virginia <i>Typha</i>	1992-'93	6.8	74.7	0.09	11.0
Virginia <i>Peltandra</i>	1992-'93	11.0	96.5	0.11	8.8
Can. Boreal Fen	1994	4.6	34.5	0.13	7.5
Can. Boreal Fen	1995	2.2	11.2	0.20	5.1
Can. Boreal Fen	1996	3.7	22.8	0.16	6.1

We have adopted the convention of expressing CH_4 emission from the wetland as a positive number, while uptake of CO_2 (net ecosystem production encompassing diel and annual variation in photosynthesis, plant respiration, and soil community respiration) is also positive. CH_4/CO_2 is the molar ratio of CH_4 emitted to CO_2 taken up. The compensation point is the value of GWP_{M} (y-axis, Figs. 2, 3) where the global warming equivalents of CO_2 uptake offsets the global warming equivalents of CH_4 emitted from each wetland.

greater uptake of carbon than the northern fen. Annual methane emission varied between 0.05 and 0.20 of the total annual CO_2 uptake (Table 1). These annual CH_4/CO_2 ratios were 2 to 6 $\times$ greater than the 0.03 value reported for the peak growing season (Whiting and Chanton, 1993). Over an annual period, an elevated CH_4/CO_2 ratio typically occurred in late summer, fall and winter as plants senesce and CO_2 uptake decreased relative to CH_4 emission.

A short-term perspective of a few decades may be an appropriate time interval when considering changes in global atmospheric and oceanic warming. Utilizing the GWP_{M} (21.8) calculated for a 20-year integration period (Lelieveld et al., 1993), the relationship of GWP_{M} with the CH_4/CO_2 ratios measured in our sites (Table 1) suggests that the wetlands could be considered greenhouse sources over the short term (Fig. 3, circles).

If long-term changes in atmospheric temperatures and sea level rise are of a primary focus, it may be appropriate to extend the integration time (Rodhe et al., 1991; IPCC, 1996). As horizon times are extended to 100 years, the GWP_{M} decreases to 7.6 (Fig. 1) and these wetlands range from sources to greenhouse gas sinks (Fig. 3, squares). This type of analysis and time interval has also been utilized to assess the contribution of peat mining and combustion on the greenhouse effect in a European mire (Rodhe and Svensson, 1995).

Over extended time horizons, the net-sink function of these wetlands for the longer-lived CO_2 molecule outweighs the release of the more potent

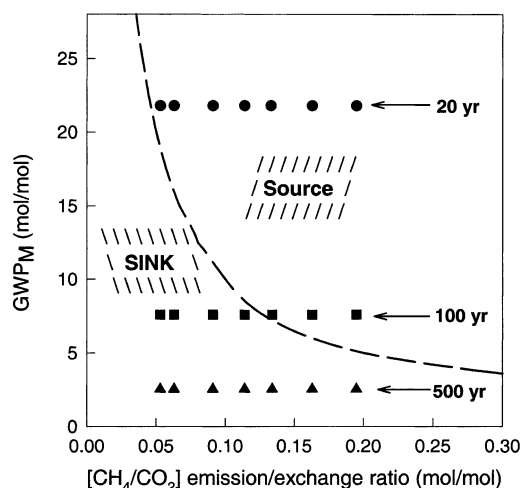


Fig. 3. The annual CH_4/CO_2 exchange ratio for Table 1 wetlands expressed on the model presented in Fig. 2. The circles, squares, and triangles represent the sites of Table 1 over 20-year ($\text{GWP}_{\text{M}} = 21.8$), 100-year ($\text{GWP}_{\text{M}} = 7.6$), and 500-year ($\text{GWP}_{\text{M}} = 2.6$) time horizons, respectively.

infrared-absorber but shorter-lived CH_4 molecule. For a 500-year horizon where GWP_{M} is 2.6 (Fig. 1), all of these wetlands could be clearly considered greenhouse gas sinks (Fig. 3, triangles). Each wetland reaches a balance point (a greenhouse compensation point) between the greenhouse equivalents of CO_2 sequestered and CH_4 emitted. We report this as the GWP_{Mcp} in which the wetland would be balanced given its current

CH₄ emission/CO₂ exchange ratio (Table 1). All the calculated GWP_{Mcp} are greater than the 2.6 GWP_M at the 500-year horizon.

The effect of climate change on wetlands is uncertain but a number of scenarios have been reviewed (Gorham, 1991). Enrichment of CO₂ has the potential to enhance CH₄ emissions from wetlands along with an increase in CO₂ fixation and biomass stocks (Billings et al., 1983; Curtis et al., 1989; Dacey et al., 1994; Hutchin et al., 1995). Uncertainty exists as to the effect of future elevated atmospheric CO₂ levels on the balance between the molar ratio of CH₄ emission and net CO₂ fixation. We have considered primarily flooded wetlands, however climate change may significantly affect the carbon cycle of wetlands by altering soil moisture and hydrology. Decreased soil moisture will probably lead to reduced CH₄ emissions but may also cause greater soil aeration. This soil aeration may elevate soil respiration and reduce the wetland's overall soil carbon sink.

Northern wetlands not only emit relatively more CH₄ in the process of sequestering CO₂ as compared to lower latitude wetlands, but they also have an extensive areal coverage (Matthews and Fung, 1987). The observed elevated CH₄/CO₂ ratio in the higher latitude wetland (Table 1) may be generated by the increased length of the winter season in the northern latitudes (when northern sites are a source of CO₂). The continued productivity of southern temperate sites during the winter contributes to their overall greater net CO₂ uptake and lower CH₄/CO₂ ratio. If the elevated CH₄/CO₂ ratio as displayed in our high latitude site holds true with more extensive data collection, then northern wetlands play a significantly greater role (on a unit area basis and areal coverage) in contributing to the radiative forcing of the atmosphere than lower latitude wetlands. However, the predicted 2 to 4°C warming in northern latitudes (IPCC, 1996) should extend the growing season, reducing the period of CO₂ loss and lead to a decrease in the CH₄/CO₂ ratio.

The creation and restoration of wetlands have increased over the past 2 decades to counter the accelerated loss of wetland ecosystems from urbanization and agricultural development (Kusler and Kentula, 1993). As the Kyoto Protocol is implemented with the development of carbon sinks to offset greenhouse gas emissions, the protection of existing peat-developing wetlands and the

restoration/creation of other wetlands to sequester carbon may be considered for carbon credits in the near future. If wetlands are to be considered for carbon credits, then the development of mitigation wetlands should be carefully designed to curtail the emission of methane while sequestering soil carbon. Ultimately, wetland soils may perform as a better long-term repository of carbon than the live-biomass of forests due to the higher disturbance regimes of forested systems as compared to wetlands (i.e., fire frequency, Gorham (1991)).

The history of atmospheric methane as determined in polar ice indicates a positive correlation of concentration change with climatic variation (Chappellaz et al., 1990; Brook et al., 2000). Long-term changes in atmospheric concentrations of CO₂ and CH₄ appear to have served as a positive feedback that enhanced warming or cooling over the last 400 kyr (Petit et al., 1999). Since CO₂ uptake is evidently coupled to methane emission (this paper; Dacey et al., 1994; Whiting and Chanton, 1993; Whiting et al., 1991a), one might expect the radiative effect of methane to be tempered, at least on a longer time scale. The increase in methane concentrations during interstadial events occurred over time periods of 100 to 300 years and maybe decoupled from temperature changes that occurred quite abruptly on a time scale of 2–4 decades (Brook et al., 1996; Brook et al., 2000). In this context, the century time horizons of GWP may be more relevant than those over decadal time scales.

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