Errors in greenhouse forcing and soil carbon sequestration estimates in freshwater wetlands: a comment on Mitsch et al. (2013)

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Abstract Radiative forcing feedbacks from wetlands have been an important component of past climate change and will likely be so in the future, so accurately assessing the carbon (C) and radiative balances of wetlands remains an important research priority. This commentary shows that the paper by Mitsch et al. (*Landscape Ecol* 28:583–597, 2013) seriously underestimated the radiative forcing effect of methane (CH₄) emissions and overestimated soil C sequestration in freshwater wetlands. The model that they used is flawed in double counting the atmospheric decay of CH₄ and incorporating a single 100 year CH₄ global warming potential. They also used a small number of sites and short-term soil dating that resulted in unrealistically high soil C sequestration rates, ignoring decay of the entire soil C pool and allochthonous inputs of C. They calculated the radiative balance instead of the radiative forcing of natural

wetlands, making their calculations irrelevant to anthropogenic climate change. Irrespective of the radiative forcing of wetlands, they provide essential ecosystem services that are important to protect.

Keywords Wetlands · Global warming potential · Radiative forcing · Methane · Soil carbon sequestration

Introduction

Management decisions in wetlands may have important consequences for global radiative forcing because of their massive soil carbon (C) pools, high methane (CH₄) emissions, and potentially high soil C sequestration rates (Bridgham et al. 2006). A recent article by Mitsch et al. (2013) addresses this theme by suggesting that soil C sequestration outweighs the warming effect of CH₄ emissions in the world's wetlands within decades to few hundred years, and that globally wetlands comprise a substantial soil C sink. However, we feel that this paper has numerous inaccuracies that have important implications for management decisions. The limitations of their analysis have also been addressed by Neubauer (2014), who reanalyzed the C flux data in Mitsch et al. (2013) with the well-established Frolking et al. (2006) model of wetland radiative forcing that includes sustained CH₄ emissions, five atmospheric carbon dioxide

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(CO₂) pools with different lifetimes, and a more defensible atmospheric CH₄ lifetime. Neubauer also included N₂O emissions in his model. He demonstrated that Mitsch et al. vastly underestimated the time required for a wetland to have a net cooling effect on the environment. While we consider the Neubauer article to be a much more appropriate estimate of wetland radiation forcing and endorse his findings, many wetland practitioners may be confused by a comparison of two models, each with its own set of assumptions. We show here that: (i) the model developed by Mitsch et al. is flawed in its conception without the need to resort to a comparison with another model, (ii) Mitsch et al. used inflated C sequestration numbers that do not represent a reasonable range of those reported in the literature, and (iii) Mitsch et al. confused the fundamental concepts of radiative forcing and radiative balance.

Limitations of the Mitsch et al. model

While we agree with (Neubauer 2014) that a model with sustained CH₄ emissions more effectively captures the radiative forcing of wetlands over time, the global warming potential (GWP) concept used by Mitsch et al. is pervasive in the scientific literature as a means to compare the radiative effects of different greenhouse gases (GHG). Hence, it is important to point out that Mitsch et al. used GWPs incorrectly. This is also stated by Neubauer but without the proof that we provide here.

Mitsch et al. constructed a simple two state-variable model that we summarize in Eqs. 1–3:

$$dM_{CH_4}/dt = F_{CH_4} - k_{CH_4}M_{CH_4} \quad (1)$$

$$dM_{CO_2}/dt = k_{CH_4}M_{CH_4} - F_{CO_2} \quad (2)$$

where M_{CH_4} and M_{CO_2} are the atmospheric masses of wetland-derived CH₄ and CO₂, respectively (units of g C m⁻²); F_{CH_4} and F_{CO_2} are the net fluxes of CH₄ and CO₂ from or into the wetland; and k_{CH_4} is the first-order decay of CH₄ in the atmosphere. The $k_{CH_4}M_{CH_4}$ term represents the oxidation of CH₄ to CO₂ in the atmosphere. Mitsch et al. then defined a total forcing from the wetland in CO₂ equivalents (CO_{2eq}) at any point over 100 years as:

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

where GWP_{CH_4} is the global warming potential of CH₄ at 100 years (i.e., 25).

However, use of GWP in this manner is fraught with problems. GWP_{CH_4} is represented mathematically as a 1 kg pulse emission of CH₄ relative to a 1 kg pulse emission of CO₂ over some time horizon TH (Forster et al. 2007):

$$GWP_{CH_4} = \frac{\int_0^{TH} RF_{CH_4}(t)dt}{\int_0^{TH} RF_{CO_2}(t)dt} = \frac{\int_0^{TH} a_{CH_4}[M_{CH_4}(t)]dt}{\int_0^{TH} a_{CO_2}[M_{CO_2}(t)]dt} \quad (4)$$

where RF is the radiative forcing and a is the instantaneous radiative efficiency due to a unit increase of the gas in the atmosphere (i.e., radiative efficiency). One can easily see in Eq. 4 that the change in M_{CH_4} over time is already incorporated into the GWP, so by using it in Eq. 3 Mitsch et al. doubled counted for the atmospheric decay of CH₄ and seriously underestimated the radiative forcing of wetlands.

The instantaneous radiative efficiency of CH₄ (a_{CH_4}) is 73 times greater than that for CO₂ (a_{CO_2}) on a mass basis (Forster et al. 2007), but this difference decreases through time because the atmospheric lifetime of CH₄ in the atmosphere is much shorter than CO₂. Thus, the GWP of a pulse of CH₄ emitted from a wetland is initially 73, at 20 years it is still 72, and at 100 years it is 25. Consequently, using a 100 year pulse-based GWP for CH₄ in a model of continuous CO₂ and CH₄ fluxes over a 100 years simulation as done by Mitsch et al. is incorrect because the majority of the CH₄ emitted over that period would have a much higher GWP. In summary, it is clear that the model of Mitsch et al. vastly underestimated the radiative forcing of CH₄ emissions from wetlands, as is shown above and by Neubauer (2014) in his reanalysis of their data using a more appropriate model.

Mitsch et al. overestimate wetland soil C sequestration

Mitsch et al. determined soil C sequestration with ¹³⁷Cs and ²¹⁰Pb dating, which are common techniques to quantify soil C sequestration over roughly the past 50–100 years. However, all peatlands and most

Table 1 A comparison of world freshwater wetland net C sequestration estimates

	Mitsch et al. (2013)			This study		
	Mineral soil wetlands ^a	Boreal peatlands	Total or weighted average	Mineral-soil wetlands	Boreal peatlands	Total or weighted average
Net C retention ($\text{g C m}^{-2} \text{ year}^{-1}$)	208	29	118	17 ^b	10.4 ^c	13.7
Wetland area $\times 10^6 \text{ km}^2$	3.5	3.5	7.0	3.5	3.5	7.0
Total C retention ($\times 10^{12} \text{ g C year}^{-1}$)	720	110	830	60	36	96

^a Includes the sum or weighted average of tropical and sub-tropical, and temperate wetlands in (Mitsch et al. 2013)

^b From Bridgman et al. (2006)

^c Net C balance during the last millennium from Yu (2012)

mineral-soil wetlands have been accumulating soil C for centuries to millennia, and that older soil C continues to undergo slow decomposition, necessitating longer term dating techniques like ^{14}C to accurately estimate whole-profile soil C sequestration rates. Indeed, rates of soil C sequestration based on ^{14}C systematically give rates $\sim 20\%$ of short-term measurements (either ^{137}Cs or ^{210}Pb) under constant accumulation conditions (Craft and Richardson 1998; Turunen et al. 2004). Thus, the sequestration values of $194 \pm 56 \text{ g C m}^{-2} \text{ year}^{-1}$ for tropical wetlands and $278 \pm 42 \text{ g C m}^{-2} \text{ year}^{-1}$ for temperate wetlands used by Mitsch et al. in their global extrapolation only reflect short-term apparent rates of C accumulation but do not take into account decomposition of older C and are likely much larger than whole-profile soil C sequestration rates. Also, all soil C sequestration estimates using dating techniques give a constant value over the time frame of reference and do not reflect the current rate, which may vary substantially over time in human-impacted systems.

Even the short-term C sequestration estimates used by Mitsch et al. are much higher than those reported in a review of rates from 26 North American mineral-soil wetlands (Bridgman et al. 2006). They found that soil C sequestration rates ranged from 0 to $616 \text{ g C m}^{-2} \text{ year}^{-1}$, with this large range probably reflecting the dating method used (as discussed above) and natural variability. The geometric mean of $17 \text{ g C m}^{-2} \text{ year}^{-1}$ was deemed to be the most reliable value. As explained in Bridgman et al. (2006), even this lower value is probably an overestimate because much of the C stored in mineral-soil wetlands may be allochthonous (i.e., derived from outside the wetland) versus autochthonous (derived from within the wetland). The

net accumulation of allochthonous C within a wetland at a landscape scale is solely dependent upon the rate of replacement of soil C in the upland source and the fractional decomposition of the allochthonous C within the wetland (Van Oost et al. 2007), although these calculations are almost never done in practice.

In contrast to mineral-soil wetlands, C in peatlands is almost entirely autochthonous, and long-term soil C sequestration (using basal and other ^{14}C dates) has been intensively studied. Based upon long-term C accumulation data reported in the literature, Bridgman et al. (2006) estimated that permafrost peatlands sequester $13 \text{ g C m}^{-2} \text{ year}^{-1}$ and non-permafrost northern peatlands sequester $19 \text{ g C m}^{-2} \text{ year}^{-1}$, which is comparable to a recent estimate of $19 \text{ g C m}^{-2} \text{ year}^{-1}$ for all northern peatlands (Yu et al. 2010). These values are averaged over the entire peat profile, but an approach using ^{14}C dates through the entire peat profile and considering long-term decomposition for 33 sites estimated a net C balance of $10 \text{ g C m}^{-2} \text{ year}^{-1}$ in northern peatlands over the last millennium (Yu 2012). In comparison, Mitsch et al. give a somewhat higher soil sequestration value of $29 \pm 13 \text{ g C m}^{-2} \text{ year}^{-1}$ for boreal peatlands that is still within the error bounds of previous estimates.

We next use the wetland areas in Mitsch et al. and our more realistic estimates of soil C sequestration rates to compare our values of global soil C retention in freshwater wetlands to those of Mitsch et al. (Table 1). We estimate that mineral-soil wetlands globally sequester $60 \text{ Tg C year}^{-1}$ and boreal peatlands sequester $36 \text{ Tg C year}^{-1}$ ($1 \text{ Tg} = 10^{12} \text{ g}$), for a global total of $96 \text{ Tg C year}^{-1}$. Comparatively, Mitsch et al. estimate that mineral-soil wetlands sequester $720 \text{ Tg C year}^{-1}$ and peatlands sequester $110 \text{ Tg C year}^{-1}$, for a total of

830 Tg C year⁻¹—a value 8.6 times higher than ours. Because most of the difference in these estimates is attributed to mineral-soil wetlands, it is useful to make a reality check of the soil C sequestration numbers in Mitsch et al. A sequestration rate of 278 g C m⁻² year⁻¹ as reported for temperate mineral-soil wetlands results in an accretion rate of 0.36 cm year⁻¹, assuming 7.7 % soil C and a bulk density of 1.0 g cm⁻³ (Batjes 1996; Smith et al. 2001). While undoubtedly some wetlands experience such high sedimentation rates in areas of high erosion over some period of time (e.g., Craft and Casey 2000), global wetlands would become uplands over centuries to millennia at this high sedimentation rate, which clearly has not happened.

While accurate estimates of C sequestration are difficult to obtain, what is clear is that Mitsch et al.'s soil C sequestration rates are from only a handful of sites and almost certainly severely overestimate C sequestration, especially when extrapolated to the global scale.

Mitsch et al. inappropriately used radiation balance instead of radiative forcing

Mitsch et al. use the term 'radiative forcing' but actually calculate the radiative balance of most of their study wetlands. Confusion about the seemingly subtle distinction between these two terms is widespread and by no means limited to Mitsch et al., but it actually has far-reaching implications for considering the role of wetlands in climate change (Bridgham et al. 2006). Radiative balance refers to the static radiative effect of GHG, whereas the radiative forcing refers to an externally (usually human) imposed perturbation on the Earth's radiative energy budget (Ramaswamy et al. 2001), i.e. it is the calculation of the perturbation relative to a quasi steady-state balance. Examining static rates of these processes in natural wetlands is relevant to anthropogenic climate change only as a baseline unless it can be shown that those rates have changed due to human activities, either directly or indirectly. Of the wetlands in the Mitsch et al. study, their analysis was demonstrably relevant to radiative forcing in only the two restored wetlands in Ohio. Mitsch et al. did correctly acknowledge this distinction in their sentence "We also showed created wetlands had CH₄ emissions lower than or comparable to natural wetlands after 13–15 years." However, in this

case they extrapolated from two restored wetlands at a single site to all restored wetlands, which we consider inappropriate evidence for this broad statement.

Conclusions

Mitsch et al. use a flawed model to calculate the radiative balance of freshwater wetlands that seriously underestimated the radiative forcing effect of wetland CH₄ emissions. They also likely greatly overestimated wetland soil C sequestration rates. Moreover, they calculated the radiative balance instead of the radiative forcing of natural wetlands, and thus their global calculations are invalid with respect to the role of wetlands in climate change. When considered from their initiation, most freshwater wetlands should eventually have a net radiative cooling effect, but this may take centuries to millennia to occur (Frolking et al. 2006; Neubauer 2014). However, marine-associated wetlands often have quite high soil C sequestration rates (Pendleton et al. 2012) and low CH₄ emissions (Bridgham et al. 2006), although many of the problems identified here in accurately assessing soil C sequestration rates in freshwater wetlands also apply to marine-associated wetlands. Additionally, forested wetlands can sequester large amounts of C in tree biomass (Mitsch and Gosselink 2000; Bridgham et al. 2006), and many have water tables that are far below the surface for extended periods during the growing season (Mitsch and Gosselink 2000), which should reduce CH₄ emissions. Thus, restoration or creation of marine-associated and forested wetlands may quite rapidly lead to a negative (i.e., cooling) radiative forcing. Importantly, peatlands comprise a huge global C pool (Bridgham et al. 2006; Yu 2012) that is critically important to protect because oxidation of that resource due to drainage will likely lead to a large positive radiative forcing, even after accounting for reduction in CH₄ emissions. Abundant evidence suggests that wetlands were an important driver of past glacial/interglacial cycles (Chappellaz et al. 1993a, b; Blunier et al. 1995; Loulergue et al. 2008) and will likely remain an important feedback to future anthropogenic climate change. For all of these reasons, accurately assessing the C and radiative balances of wetlands remains an important research priority. Moreover, we strongly agree with the conclusion of Mitsch et al. that "Because wetlands provide many

ecosystem services in addition to C sequestration, it is shortsighted to suggest that wetlands should not be created or restored because of their [GHG] emissions.”

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