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On the challenges of modeling the net radiative forcing of wetlands: reconsidering Mitsch et al. 2013

Scott C. Neubauer
Virginia Commonwealth University, sneubauer@vcu.edu

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Scott C. Neubauer

Department of Biology, Virginia Commonwealth University,

1000 West Cary St.,

Richmond, Virginia 23284, USA

e-mail: sneubauer@vcu.edu

phone: 804-827-2794/fax: 804-828-0503

ABSTRACT

Wetlands play a role in regulating global climate by removing carbon dioxide (CO_2) from the atmosphere and sequestering it as soil carbon, and by emitting methane (CH_4) and nitrous oxide (N_2O) to the atmosphere. In a recent article in this journal (Mitsch et al. 2013. 28:583-597), CO_2 sequestration and CH_4 emissions were modeled for several freshwater wetlands that vary in vegetation type, climate, and hydrology. The authors of that study made significant errors that caused them to underestimate the importance of wetland CH_4 emissions on climate dynamics. Here, I reanalyze the Mitsch et al. dataset and show that all of their wetlands had an initial warming effect but eventually caused negative net radiative forcing within ~60-14,000 years, depending on the ratio of CO_2 sequestration to CH_4 emissions. The addition of a N_2O component to the model suggested that typical wetland N_2O emission rates would contribute only a minor burden to wetland radiative forcing, although specific application of this three-gas model is limited by the paucity of sites where CO_2 sequestration, CH_4 emission, and N_2O exchange rates have all been measured. Across the landscape, many natural wetlands may already cause negative net radiative forcing when integrated over their lifetime. However, caution should be applied when using carbon sequestration as a rationale for designing wetland construction and restoration projects since freshwater wetlands may have a net positive (warming) effect on climate for decades to centuries or longer.

KEYWORDS

carbon sequestration, climate change, created wetlands, global warming potential, modeling, radiative efficiency, restored wetlands, swamp, tidal freshwater marsh

INTRODUCTION

Wetlands occupy a broad landscape niche that spans tropical to boreal regions, freshwater to saline conditions, and always-wet to seasonally-dry environments. Across their range, wetlands provide a multitude of ecosystem services such as improving the quality of surface waters, serving as habitat for a wide variety of flora and fauna, and providing flood control. Wetlands also play a key role in climate regulation. High rates of wetland primary production result in the fixation of considerable amounts of atmospheric carbon dioxide (CO_2) into plant biomass. Much of the fixed carbon (C) is returned to the atmosphere as plant materials decompose, but some is resistant to decomposition and contributes to the significant amounts of C stored in wetland soils (Mitra et al. 2005). In typical freshwater wetland soils, methane (CH_4) is produced during decomposition, with natural wetlands accounting for ~20-30% of global CH_4 emissions (Conrad 2009; Bridgham et al. 2013). An examination of the balance between rates of CO_2 sequestration and CH_4 emissions can provide insights into the role of wetlands in global climate dynamics.

In a recent paper in this journal, Mitsch et al. (2013) presented a C model that followed the fate of CH_4 emitted from a variety of freshwater wetlands and also accounted for the uptake of CO_2 from the atmosphere and its sequestration in wetland soils. Based on their modeling efforts, Mitsch et al. reported that roughly half of the wetlands they examined were net greenhouse gas sinks from their creation or within 20 years. Nearly all of the wetlands became greenhouse gas sinks within a 300-year period, leading Mitsch et al. to suggest that rapid CH_4 oxidation in the atmosphere has the effect of minimizing the importance of CH_4 emissions from wetlands.

In this article, I re-analyzed the CO_2 sequestration and CH_4 emission data presented in Mitsch et al. (2013) using a revised model that more robustly and correctly describes the atmospheric dynamics of these gases. Specifically, the model described below includes a

description of processes that moderate perturbations in atmospheric CO_2 budgets, an important feedback that was missing from the Mitsch et al. model. Additionally, Mitsch and coauthors inappropriately used the global warming potential to determine the amounts of warming (due to CH_4 emissions) and cooling (due to soil C sequestration) attributable to their study wetlands. Collectively, these issues led Mitsch et al. (2013) to substantially underestimate the radiative forcing from freshwater wetlands.

METHODS

Study wetlands

The model described below was run using annual CH_4 emission rates and soil C sequestration rates for the three humid temperate (Olentangy 1 and 2, Old Woman Creek), two humid tropical (Earth University and La Selva), and two dry tropical wetlands (Palo Verde, Okavango) that were studied by Mitsch et al. (2013; see Table 1 in that citation for site details). I also ran the model for an eighth site (Sweet Hall), a tidal freshwater marsh on the Pamunkey River, Virginia where I have measured an average annual CH_4 emission rate of 72 g C m^{-2} y^{-1} and a C sequestration rate of 224 g C m^{-2} y^{-1} (Neubauer et al. 2000; 2002).

Model structure

The model presented in Mitsch et al. (2013) tracked the fate of CO_2 and CH_4 in a hypothetical 1 m x 1 m column of atmosphere over a wetland. Below, I present a revised model that is based on Frolking et al. (2006), with some differences that are discussed below (see Figs. 1 in Mitsch et al. 2013 and Frolking et al. 2006 for general structure of each model). Methane produced in wetland soils is emitted at a rate of $F_{CH4\text{-}C}$ (g C m^{-2} y^{-1}). Methane has a mean atmospheric perturbation lifetime (τ_{CH4}) of 12 years (Forster et al. 2007), with its loss primarily

due to reaction with the hydroxyl free radical (OH), resulting in the production of CO_2. This 12-year lifetime is somewhat longer than the 7-year half-life (equivalent to a 10-year lifetime) used by Mitsch et al. (2013). The inventory of wetland-derived CH_4 at any time ($M_{CH4\text{-}C,(t)}$; g C m^{-2}) is a function of the existing inventory of wetland-derived atmospheric CH_4 ($M_{CH4\text{-}C,(t\text{-}1)}$), the rate of CH_4 emission from wetlands ($F_{CH4\text{-}C}$), and its destruction/removal in the atmosphere:

$$M_{CH4-C,(t)} = F_{CH4-C}dt + \left[M_{CH4-C,(t-1)} \times e^{(-dt/\tau_{CH4})}\right], \quad (1)$$

where dt (y) is the time step of the model (0.2 y).

Atmospheric CO_2 fixed by wetland primary producers can be sequestered in soils or plants at a rate $F_{seq\text{-}C}$, emitted as CH_4 at a rate $F_{CH4\text{-}C}$, or returned to the atmosphere as CO_2. Thus, the net rate of CO_2 uptake by the wetland can be approximated as $F_{CO2\text{-}C} = F_{seq\text{-}C} + F_{CH4\text{-}C}$ (g C m^{-2} y^{-1}). This model, like other similar ones (Frolking et al. 2006; Mitsch et al. 2013), does not explicitly consider other sources or sinks of wetland C (e.g., dissolved organic and inorganic C, allochthonous materials). Following Shine et al. (2005) and Frolking et al. (2006), atmospheric CO_2 was modeled as five non-interacting reservoirs with lifetimes of 3.4 y to 1×10^8 y. Treating atmospheric CO_2 as a single homogeneous reservoir does a poor job of capturing its temporal dynamics following perturbation (Shine et al. 2005; Forster et al. 2007). Following CO_2 fixation by the wetland, CO_2 from an implied "infinite" reservoir (e.g., the ocean) was transferred to each of the modeled CO_2 pools, with the rate of transfer modeled as a first-order function of the lifetime of each reservoir, in order to simulate the processes that add (or remove) CO_2 in response to perturbations in the equilibria between the atmosphere and biosphere, hydrosphere, and geosphere (Walker 1991; Siegenthaler and Sarmiento 1993).

The inventory of atmospheric CO_2 ($M_{CO2\text{-}C,(t)}$; g C m^{-2}) is then a function of the existing inventory of CO_2 ($M_{CO2\text{-}C,(t\text{-}1)}$), the rate of CO_2 uptake (or release) by the wetland ($F_{CO2\text{-}C}$; g C m^{-2}

y^{-1}), the production of CO_2 via the oxidation of atmospheric CH_4 (CH_{4_ox}; g C m^{-2}), and the equilibrium processes that adjust concentrations in response to atmospheric perturbations. The inclusion of a CH_4 oxidation term parallels the model of Mitsch et al. (2013); the Frolking et al. (2006) model did not include this process. Changes in each of the five atmospheric CO_2 reservoirs are calculated separately, and then summed to determine the total CO_2 pool:

$$M_{CO2-C,(t)} = \sum_{i=1}^{5} f_i\left(F_{CO2-C}dt + CH_{4\_ox}\right) + \left[M_{CO2-C\_i,(t-1)} \times e^{(-dt/\tau_{CO2\_i})}\right], \quad (2)$$

where τ_{CO2_i} is the perturbation lifetime (y) and f_i is the relative fractional size of reservoir i (Frolking et al. 2006). When a wetland is a net sink for atmospheric CO_2, $F_{CO2\text{-}C}$ has a negative value. CH_{4_ox} is the $\left[M_{CH4-C,(t-1)} \times e^{(-dt/\tau_{CH4})}\right]$ term from equation 1.

At each time step, the model calculated the radiative forcing due to atmospheric CO_2 and CH_4 using radiative efficiencies of 1.79×10^{-15} W m^{-2} (kg CO_2)$^{-1}$ and 1.3×10^{-13} W m^{-2} (kg CH_4)$^{-1}$ (Forster et al. 2007), which represent the change in Earth's energy balance per unit area per mass of gas. The radiative efficiency for CH_4 was multiplied by 1.3 to account for indirect forcings of CH_4 on the radiation balance (e.g., the effects of CH_4 on tropospheric ozone and stratospheric water vapor levels; Shine et al. 2005; Forster et al. 2007), a standard practice in CH_4 radiative forcing models. The CO_2 and CH_4 pools, which were modeled using units of grams of C, were converted to kg CO_2 and kg CH_4, respectively, before applying the radiative efficiency values.

Mitsch et al. (2013) incorrectly accounted for the radiative effects of CH_4 and CO_2 by applying the global warming potential for CH_4 (GWP_{CH4}) to their modeled changes in the inventory of this gas. However, the atmospheric models used to generate GWP_{CH4} values include a decay coefficient similar to τ_{CH4} (equation 1) to capture the kinetics of atmospheric CH_4 oxidation. By including GWP_{CH4} in their model and specifically modeling atmospheric CH_4 dynamics, Mitsch et al. (2013) underestimated radiative forcing by double-counting CH_4 decay

in the atmosphere. Further, by definition the global warming potential assesses the impact of a greenhouse gas pulse (relative to CO_2), integrated over a defined time period, and is therefore inappropriate for determining radiative forcing in sustained emission/uptake scenarios (Frolking et al. 2006) or for inferring radiative forcing at a single point in time.

Following Frolking et al. (2006), the time that net radiative forcing changes from positive (net warming) to negative (net cooling) is termed the radiative forcing switchover time. The instantaneous switchover time considers the radiative forcing due to CH_4 emissions and the cooling effect due to CO_2 uptake at a moment in time, whereas the cumulative switchover time reflects greenhouse gas dynamics integrated over the entire history of the wetland.

RESULTS AND DISCUSSION

Model dynamics

The temporal changes in radiative forcing of wetland-influenced atmospheric CO_2 and CH_4 pools depend on rates of wetland CO_2 uptake and CH_4 emission, and the dynamics of these gases in the atmosphere. Under a constant CH_4 emission scenario with a first-order decay term as modeled here, the reservoir of wetland-derived CH_4 reaches steady state (inputs = outputs) after roughly 50 years (~4 lifetimes; Fig. 1A); after this point, the instantaneous radiative forcing due to CH_4 remains roughly constant through the remainder of the simulation although cumulative radiative forcing increases over the lifetime of the wetland (compare 'CH_4' lines on Fig. 1A and 1B). In contrast to the CH_4 pool, atmospheric CO_2 never reaches steady state in the model because it is treated as five distinct pools (Fig. 1A), one of which reaches equilibrium only on geological time scales. As a consequence, the instantaneous radiative forcing due to CO_2 decreases (i.e., becomes more negative) throughout the simulation.

The combined non-linear dynamics of the CO_2 and CH_4 pools determine when the radiative forcing switchover time occurs. The instantaneous net radiative forcing of the system peaks as the CH_4 reservoir approaches steady state and then declines steadily, eventually switching from positive (net warming effect) to negative (net cooling) (Fig. 1A). At the instantaneous radiative forcing switchover time, the cumulative radiative forcing is at near-maximum values (Fig. 1B), with the cumulative radiative forcing switchover time occurring about two times later than the instantaneous switchover time. For the community of wetland practitioners and landscape managers concerned about the effects that natural, restored, and constructed wetlands have on climate dynamics, the cumulative switchover time provides a more relevant indicator of the long-term warming or cooling effect of a site and will be used in subsequent analyses and discussion.

Gases that are produced or consumed by wetlands are subject to non-biological processes that regulate their atmospheric abundance (and therefore radiative forcing). The removal of CH_4 is largely due to chemical oxidation in the atmosphere, resulting in CO_2 production; minor sinks include biological oxidation in terrestrial soils and loss to the stratosphere (Forster et al. 2007). The model used here does not distinguish between the mechanisms that contribute to atmospheric CH_4 losses. Similarly, the model includes equilibrium feedbacks that dampen fluctuations in the atmospheric CO_2 pool but does not parse specific processes such as the concentration-gradient driven flux of CO_2 between ocean and atmosphere (Siegenthaler and Sarmiento 1993) or the longer-term equilibration of the atmosphere with soils, the deep ocean, and geological reservoirs (Walker 1991).

Mitsch et al. (2013) made several modeling decisions that caused them to greatly underestimate radiative forcing switchover times. By reproducing their model and comparing it with the one described herein, I determined that their incorrect application of global warming

potentials caused them to underestimate switchover times by a factor of ~4-9 for most sites and erroneously conclude that two of their primary study sites always caused negative net radiative forcing (Fig. 2B). Excluding the atmospheric CO_2 feedbacks discussed above contributed to an overemphasis of the wetland CO_2 sink, leading Mitsch et al. to underestimate switchover times by an additional factor of 2-5 (Fig. 2B). The combined effect is that the Mitsch et al. model incorrectly suggested that some wetland sites caused negative net radiative forcing from their creation (when, in fact, they would contribute positive net radiative forcing for ≥60 years) and underestimated the true radiative forcing switchover time for other wetlands by >94% (a factor of ~19-27). Additionally, Mitsch et al. (2013) used an uncited 7-year half-life (10-year lifetime) for CH_4 and not the 12-year lifetime from the latest report from the Intergovernmental Panel on Climate Change (Forster et al. 2007). Mitsch et al.'s use of a shorter lifetime, which is equivalent to a faster CH_4 removal rate, discounted the effect of wetland CH_4 emissions and reduced switchover times by 15-17% (not shown). Thus, the differences in output between the model presented here and that of Mitsch et al. (2013) were primarily due to their misuse of global warming potentials and secondarily affected by the absence from their model of equilibrium processes that affect the atmospheric CO_2 pool, with a relatively minor effect from their choice for the lifetime (half-life) of atmospheric CH_4.

Wetland greenhouse gas dynamics

All of the wetlands that were modeled herein caused lifetime negative net radiative forcing, with cumulative radiative forcing switchover times ranging from 61 y (Olentangy 1 wetland) to 14,049 y (Palo Verde site); none of the wetlands was a net greenhouse gas sink at the start of a model run (Fig. 2A). These switchover times were two times longer than the instantaneous switchover times (mean ratio = 2.0 ± 0.1) for the study sites. A wetland would immediately

cause negative net radiative forcing at CO_2 uptake:CH_4 emission ratios ≥94 g CO_2:g CH_4 (equivalent to the x-intercept of 91 g CO_2 sequestered per g CH_4 emitted on Fig. 2). Note that this value could have been predicted a priori based on the ratio of radiative efficiencies for CO_2 and CH_4 (94.4 g CO_2:1 g CH_4, after accounting for the indirect effects of CH_4). In contrast, at a sequestration to emission ratio of 0.6 g CO_2:g CH_4, a wetland would have an integrated lifetime warming effect on the climate for >20,000 years. As demonstrated by Frolking et al. (2006), there is a non-linear relationship between the switchover time and the ratio of CO_2 sequestration (or uptake) to CH_4 emissions, with longer switchover times occurring when this ratio is low.

The model presented here indicates that a site with a sequestration to emission ratio of 78, 38, or 13 g CO_2:g CH_4 would lead to negative net radiative forcing after 20, 100, or 500 years, respectively. These ratios exceed the global warming potential of CH_4 (72, 25, and 7.6 over the same time periods), emphasizing that a metric designed for pulse emissions (global warming potential) is inappropriate for sustained flux scenarios.

There is considerably more knowledge of wetland CO_2 sequestration and CH_4 emission rates than there is for fluxes of gases such as nitrous oxide (N_2O). Wetlands may be sources or sinks of atmospheric N_2O, although their importance in this capacity is poorly understood at all levels, from individual sites up to the global extent of wetlands. Due to its infrared characteristics and long atmospheric lifetime (114 y), N_2O has a higher global warming potential than CH_4 (298 vs. 25 over a 100 y period; Forster et al. 2007). In an initial effort to determine how simultaneous emissions of both CH_4 and N_2O would affect the cumulative radiative forcing switchover time, the model was expanded to include N_2O dynamics using the aforementioned lifetime and a radiative efficiency of 3.87×10^{-13} W m^{-2} (kg N_2O)$^{-1}$ (Forster et al. 2007). This revised model indicates that wetlands cause negative net radiative forcing at CO_2:N_2O ratios >314 (if CH_4

emissions are set to zero). As rates of N_2O emissions increase, the radiative switchover time increases in roughly exponential fashion such that a wetland with a CO_2:N_2O ratio ≤ 50 would require over 4,600 years to reach the radiative forcing switchover time (not shown).

Fluxes of N_2O that are too low to force a net warming effect in the absence of CH_4 can affect the radiative forcing switchover time when the interactions between all three greenhouse gases are considered (Fig. 3). A recent compilation of wetland N_2O emission rates found a median flux of 2.7 μg N_2O m^{-2} h^{-1} (range: -0.8 to 4167 μg N_2O m^{-2} h^{-1}, n = 26 sites; Moseman-Valtierra 2012). Assuming a typical wetland CO_2 sequestration rate of ~200 g C m^{-2} y^{-1} (after Craft 2007; Mitsch et al. 2013), this median N_2O emission rate is equivalent to a CO_2:N_2O ratio of ~30,000 g CO_2:g N_2O. This rate of N_2O emission, on its own, is offset by the cooling effect of wetland CO_2 sequestration. However, when acting in concert with CH_4 emissions that are typical of the wetlands studied here (0.9 to 50 g CO_2:g CH_4; Fig. 2), N_2O emissions at a relative rate of 30,000 g CO_2:g N_2O can increase the radiative switchover time by up to 5 years as a non-linear function of the CO_2:CH_4 ratio (Fig. 3). As N_2O emission rates increase, the change in the switchover time gets larger such that the switchover time increases by up to 470 years at a CO_2:N_2O ratio of 300 g CO_2:g N_2O. The highest N_2O uptake rate reported in the Moseman-Valtierra (2012) synthesis would decrease the switchover time by ~20 to 4,000 y across the study wetlands (see -1,000 g CO_2:g N_2O line on Fig. 3). The patterns across CH_4 emission rates and levels of N_2O uptake or release are non-linear, indicating the level of complexity involved in forecasting the combined effects of wetland CH_4 and N_2O fluxes on global radiative forcing.

CONCLUSIONS

This reanalysis of wetland CO_2 and CH_4 dynamics supports the general conclusion of Mitsch et al. (2013) that most wetlands will eventually cause negative net radiative forcing.

However, for the temperate and tropical wetlands studied herein, cumulative switchover times ranged from 61 to 14,049 years, which is considerably longer than the <300 y timeframe reported by Mitsch et al. (2013). The difference primarily reflects Mitsch et al.'s inappropriate use of the global warming potential and the exclusion from their model of processes that buffer perturbations in atmospheric CO_2 budgets.

Across the landscape, many natural wetlands may already be greenhouse gas sinks on a lifetime basis (e.g., northern peatlands, Frolking and Roulet 2007). Further, no natural wetlands older than ~250 years can be considered sources of net radiative forcing (barring changes that modify a site's greenhouse gas budget) because their emissions are part of the pre-industrial era baseline that is used for climate accounting purposes. In contrast, newly created wetlands will contribute to global radiative forcing for the first portion of their lifetime unless the projects can be designed to maximize CO_2 sequestration and/or minimize CH_4 and N_2O emissions. A short-to-moderate timeframe (~decades) may be appropriate for judging the "success" of wetland creation efforts (Mitsch and Wilson 1996), but a full accounting of climate change consequences may not be realized for hundreds to thousands of years. Because climate regulation is only one of many wetland ecosystem services, this should not be interpreted as an argument against the creation and restoration of wetlands. Still, the analyses presented herein suggest that caution should be applied when designing wetland projects since freshwater wetlands may have a net positive (warming) effect on climate for decades to centuries or longer.

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FIGURE LEGENDS

Fig. 1. Wetland radiative forcing over a 1000 y period, using Sweet Hall marsh (Virginia) as an example. (A) Instantaneous radiative forcing by CH_4, CO_2 (including the five atmospheric CO_2 pools), and the combined (net) CO_2+CH_4 effect. (B) Cumulative radiative forcing of CO_2 and CH_4 (individually and combined), plus the instantaneous net radiative forcing. The "CO_2+CH_4, instantaneous" curves in panels A and B are the same. fW = 10^{-15} watts, pW = 10^{-12} watts.

Fig. 2. (A) Relationship between the cumulative radiative forcing switchover time and the ratio of CO_2 sequestered to CH_4 emitted. The dotted line was calculated by running the model with CO_2:CH_4 ratios spanning the range from 0.2 to >100 g CO_2:g CH_4. (B) Effects of modeling choices on cumulative radiative forcing switchover times. Symbols correspond to the same sites shown in panel A. The distance denoted as *i* indicates the increase in switchover time when CO_2 feedbacks are included in the model; the distance *ii* shows the effects of correctly using radiative efficiencies (RE) instead of incorrectly applying global warming potentials (GWP). The "w/ CO_2 feedbacks, RE" curve is the same as the curve in panel A. The "no CO_2 feedbacks, GWP" curve is calculated following Mitsch et al. (2013), with the differences that the curve here shows cumulative switchover times and uses a 12-y lifetime for CH_4, whereas Mitsch et al. (2013) reported instantaneous switchover times and used a 7-y CH_4 half-life. Running the model with the 7-y half-life would reduce switchover times by ~15-17% relative to those shown here.

Fig. 3. Changes in the cumulative radiative forcing switchover time as a function of the ratios of CO_2:CH_4 and CO_2:N_2O. Negative CO_2:N_2O ratios indicate N_2O uptake by the marsh. The gray shading indicates the range of CO_2:CH_4 ratios encompassed by the wetlands that were analyzed in this study. The range of CO_2:N_2O ratios encompasses all but the most extreme N_2O flux rates reported in Moseman-Valtierra (2012).

Figure 1

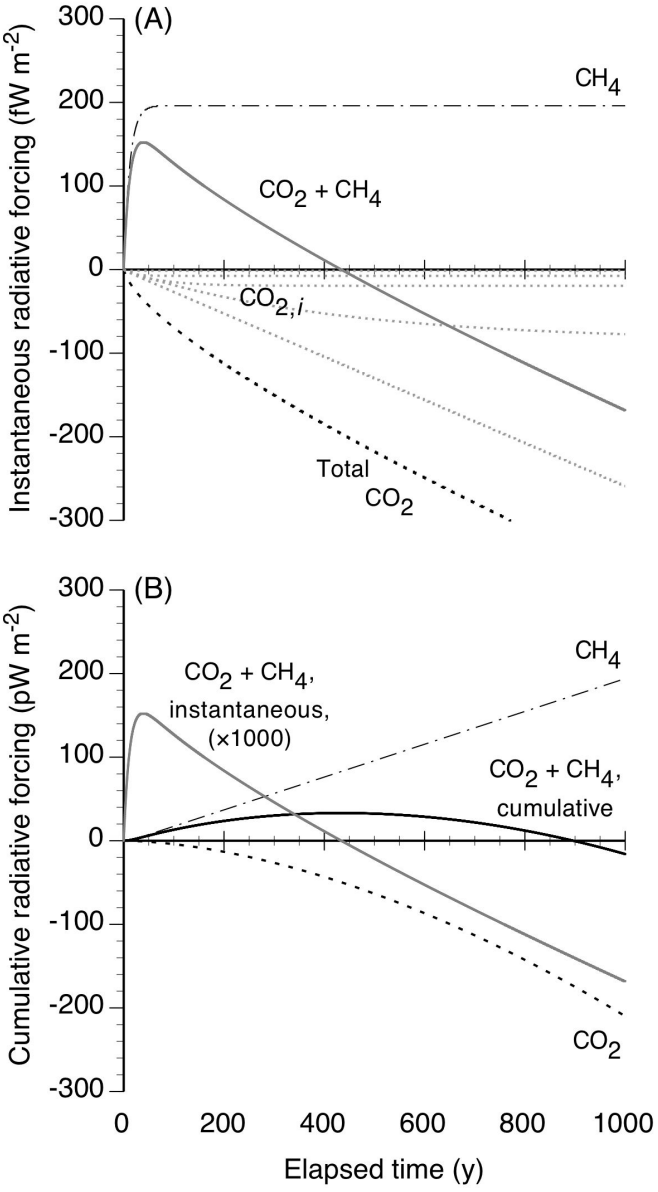
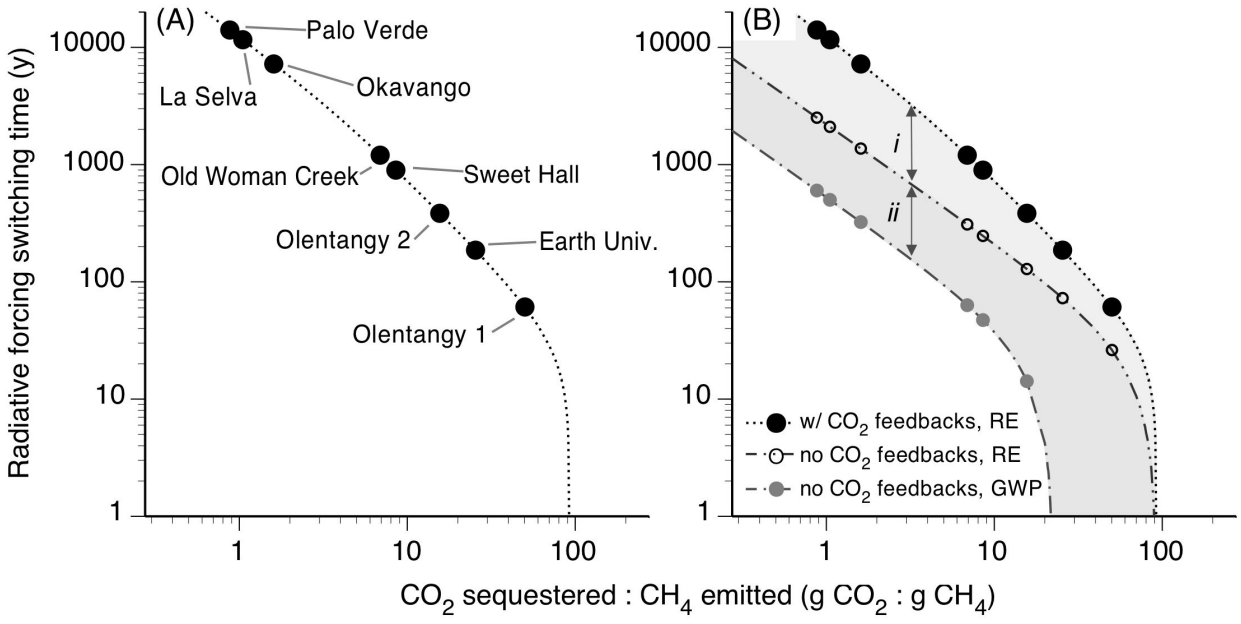
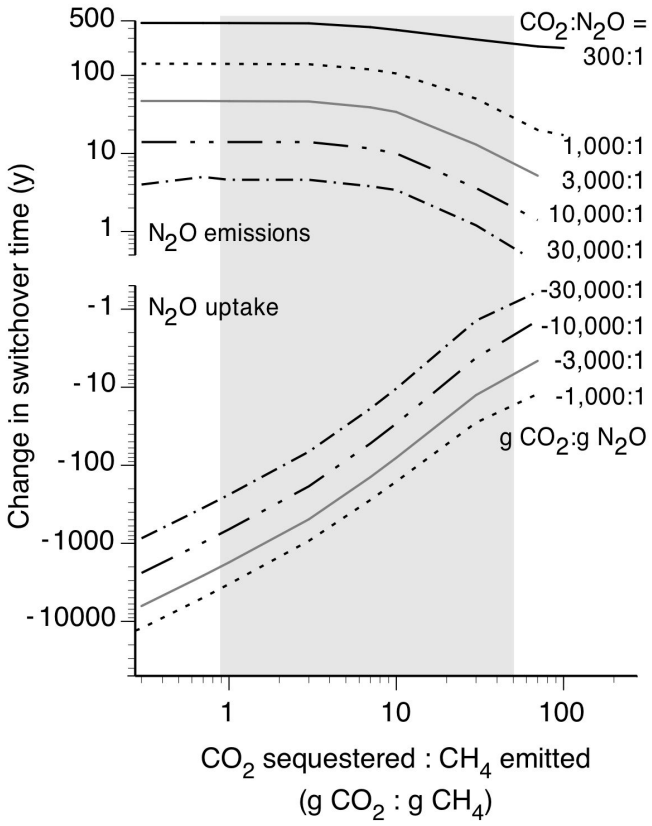


Figure 2



290 **Figure 3**



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