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Methane Emissions from Natural Wetlands in the United States: Satellite-Derived Estimation Based on Ecosystem Carbon Cycling

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ABSTRACT: Wetlands are an important natural source of methane to the atmosphere. The amounts of methane emitted from inundated ecosystems in the United States can vary greatly from area to area. Seasonal temperature, * Corresponding author address: Dr. Christopher Potter, NASA Ames Research Center, Mail Stop 242-4, Moffett Field, CA 94035.
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water table dynamics, and carbon content of soils are principal controlling factors. To calculate the effect of wetlands (and their potential conversion to other land uses) on global greenhouse gas emissions, information on area covered by various wetland types is needed, along with verified projections of spatial variation in net methane emissions. Both of these variables are poorly known, and estimates are largely unavailable at the country level. Nationwide satellite datasets for the coterminous United States (excluding Alaska) have been combined with ecosystem model predictions of monthly net carbon exchange with the atmosphere to produce the first detailed mapping of methane fluxes from natural wetlands on a monthly and annual basis. The Carnegie–Ames–Stanford Approach (CASA) model’s predicted mean emission flux of methane from wetlands of the continental United States totaled 5.5 Tg CH$_4$ per year. Ranked in terms of total annual flux, the 10 states with the highest predicted emissions (not considering Alaska) are all located in the Great Lakes region and the southern coastal regions of the country.

**KEYWORDS:** Methane; Wetlands; Landsat

1. **Introduction**

Methane (CH$_4$) is a greenhouse gas second in importance only to carbon dioxide in terms of anthropogenic warming. Globally, approximately 80% of methane production is biogenic (natural and cultivated wetlands, enteric fermentation, and waste disposal from animals), whereas 20% comes from anthropogenic sources such as leakage from landfills, natural gas production, and coal mining (Houweling et al. 1999). A study by Mikaloff Fletcher et al. (Mikaloff Fletcher et al. 2004) suggested a large contribution globally of CH$_4$ flux from swamps and biomass burning, with relatively low estimates of emissions from bogs and landfills. These study results lead to the hypothesis that the 1998 CH$_4$ growth rate anomaly was caused in part by a large increase in CH$_4$ production from wetlands.

Information is available to quantify anthropogenic CH$_4$ sources for the continental United States, including direct emissions from animal sources and rice cultivation (Energy Information Administration 2004). In contrast, neither extrapolation estimates from site-based flux measurements nor ecosystem process modeling efforts have yet to produce reliable predictions of total methane emissions from natural wetlands on a national scale. A “bottom-up” methane emission estimate for the U.S. wetland areas is currently lacking for integration with data assimilation approaches for greenhouse gases, analysis of atmospheric concentration measurements, and inversion modeling methods (Wofsy and Harriss 2002).

Net carbon fixation in flooded wetlands is strongly coupled to CH$_4$ production and emission to the atmosphere (Whiting and Chanton 2001). For example, Christensen et al. (Christensen et al. 1996) estimated CH$_4$ emissions from wetlands as a function of plant production, soil temperature, and vegetation type. According to Whiting and Chanton (Whiting and Chanton 1993), the amount of CO$_2$ exchanged on a daily basis during the peak growing season months 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. Results from measurements in peatlands of the Hudson Bay lowlands indicate the importance of primary productivity in controlling CH$_4$ emissions (Klinger et al. 1994). This process can be strongly influenced by the wet-
land’s seasonal hydrologic regime and water table effects on methane oxidation rates (Moore et al. 1990; Bubier et al. 1993b; Romanowicz et al. 1995).

Net ecosystem production (NEP) is net primary production minus gaseous carbon loss from dead plant residues and soil carbon mineralization. A survey of measured gas fluxes by Whiting and Chanton (Whiting and Chanton 2001) implied that the CH$_4$ emission flux derived from the maximum monthly NEP is representative of growing season CH$_4$ emissions. This flux is moderated by climate controls (namely, temperature) to generate the year-round CH$_4$ emissions. Rather than CH$_4$ emission going to zero during fall–winter–spring months when NEP is near zero or negative, CH$_4$ production in a wetland soil or sediment can be relatively active outside of the main growing season months.

A number of studies have shown that soil temperature influences the rate of methane production in wetlands (e.g., Bartlett and Harriss 1993; Frolking and Crill 1994; Christensen et al. 1995; Werner et al. 2003). Wetland production rates of methane have been estimated to increase logarithmically with temperature (Walter and Heimann 2000). A review by Zhuang et al. (Zhuang et al. 2004) of high-latitude wetland studies showed that a $Q_{10}$ coefficient of 3.5 was the value most commonly reported for methane production response to soil temperature.

2. Modeling approach

For this study, we have generated nationwide NEP predictions from a wetland ecosystem model called the Carnegie–Ames–Stanford Approach (CASA; Potter et al. 2001; Potter 1997), which estimates net monthly carbon flux and mineralization under (near) water-saturated soil conditions at the surface. The model includes interactions of gas flux controls: carbon substrate availability, soil moisture, soil temperature, and microbial activity.

CASA uses the fractional absorption of photosynthetically active radiation (FPAR) as the integrated vegetation “greenness” index, derived from the Advanced Very High Resolution Radiometer (AVHRR) satellite sensor at 8-km spatial resolution (Knyazikhin et al. 1998). Monthly net primary production (NPP) flux of atmospheric CO$_2$ by plants is predicted by assimilation of FPAR, modified by monthly surface solar irradiance $S_r$ and stress scalar terms for temperature $T$ and moisture $W$ effects [Equation (1)]:

$$NPP = S_r \times FPAR \times e_{\text{max}} \times T \times W.$$  (1)

Mean monthly climate data (air surface temperature, precipitation, and solar radiation flux) from the Vegetation–Ecosystem Modeling and Analysis Project (VEMAP) modeling experiment (Kittel et al. 2000) were used as model inputs to Equation (1). The light utilization efficiency term $e_{\text{max}}$ is set uniformly at 0.39 g C MJ$^{-1}$ PAR, a value that is derived from calibration of predicted annual NPP to previous field estimates (Potter et al. 1993). This model setting has been validated globally by comparing predicted annual NPP to more than 1900 field measurements of NPP (Potter et al. 2003). The CASA $e_{\text{max}}$ term has been validated also for boreal wetland sites (Amthor et al. 2001; Potter et al. 2001).

Mean monthly NEP is computed as NPP carbon gains minus total heterotrophic CO$_2$ emissions from soil microbial respiration. First-order equations were used to
simulate heterotrophic respiration fluxes of \( \text{CO}_2 \) and exchange of decomposing plant residue (metabolic and structural fractions) at the soil surface, together with surface soil organic matter (SOM) fractions that presumably vary in age and chemical composition (Potter 1997). To mimic the elevated water table conditions of wetlands and seasonal effects of inundation in slowing soil heterotrophic \( \text{CO}_2 \) emissions, monthly VEMAP (Kittel et al. 2000) precipitation inputs to the soil surface were augmented by 50% over long-term monthly values in these simulated CASA wetland runs. This adjustment is made to capture the importance of seasonal hydrologic regimes. Potter et al. (Potter et al. 2001) reported that this magnitude of augmented water run-on to a simulated wetland location was suitable to reproduce the typical measured pattern of seasonal water table fluctuations in northern forested sites.

To estimate the maximum growing season methane emission flux \( (\text{CH}_4_{\text{max}}) \), the CASA wetland model’s maximum monthly estimate of NEP for the year (Potter et al. 2001) at every 8-km grid cell was multiplied by a uniform \( \text{CH}_4 : \text{CO}_2 \) conversion factor of 0.033 determined by Whiting and Chanton (Whiting and Chanton 1993) from growing season measurements across numerous U.S. study sites.

The adjusted net \( \text{CH}_4 \) emission flux (including soil oxidation effects) for all other months of the year was computed as

\[
F_{\text{CH}_4} = \text{CH}_4_{\text{max}} \times Q_{10_{\text{CH}_4}},
\]

where \( Q_{10_{\text{CH}_4}} = 3.5^{[(T_a - T_r)/10]} \), \( T_a \) is monthly mean temperature, and \( T_r \) is the reference temperature for any 8-km grid cell. The value for \( T_r \) is taken as the mean temperature reported for the month during which \( \text{CH}_4_{\text{max}} \) is predicted for the year.

It is important to note that the previously reported \( \text{CH}_4 : \text{CO}_2 \) conversion factor of 0.033 from Whiting and Chanton (Whiting and Chanton 1993) was measured primarily during the seasonal peak of net daily ecosystem production and methane emission. However, Whiting and Chanton (Whiting and Chanton 2001) pointed out that annual \( \text{CH}_4 : \text{CO}_2 \) exchange rates could better integrate the development and senescence of plant carbon equivalents associated with \( \text{CH}_4 \) emission, which can vary over the seasons of any given year and provide variable amounts of substrates for methanogens. To test this assumption, these authors reported the results of \( \text{CO}_2 \) and \( \text{CH}_4 \) emission measurements within wetlands extending from the subtropics of Florida to a temperate wetland of Virginia to a boreal forest of Alberta, Canada. They found that the annual \( \text{CH}_4 : \text{CO}_2 \) conversion factors were 2 to 6 times greater than the 0.033 ratio value reported for the peak growing season by Whiting and Chanton (Whiting and Chanton 1993). Over an annual period, an elevated \( \text{CH}_4 : \text{CO}_2 \) ratio typically occurred in late summer, fall, and winter as plants senesced and \( \text{CO}_2 \) uptake decreased relative to \( \text{CH}_4 \) emission. We have attempted to capture this same effect in Equation (2) of elevated \( \text{CH}_4 : \text{CO}_2 \) emission ratios outside the growing season peak period by incorporation of the \( Q_{10_{\text{CH}_4}} \) term, which is designed to make the same seasonal adjustment in the \( \text{CH}_4 : \text{CO}_2 \) emission ratio (as observed by Whiting and Chanton 2001) widely applicable to wetlands across the North American continent.
3. Results

Assessment of the model’s predicted methane fluxes should be based ideally on comparisons to measured emission flux estimates at study sites across the continent. However, the spatial extent of our predicted gas emission rate from the CASA model is inherently an integrated wetland carbon flux covering an area of more than 50 km² per pixel for the ecosystem processes simulated. This large area coverage of all CASA model inputs makes validation impractical using relatively small-scale (covering less than several meters squared) plot measurements of methane emission flux.

Moreover, nearly all small-scale measurement studies in the continental United States reviewed by Bartlett and Harriss (Bartlett and Harriss 1993) report a range of estimated CH₄ emissions over one to two orders of magnitude. Measured methane fluxes can vary enormously from one location to another within the same study area, depending on microtopographic influences on surface water and biogeochemistry (Bubier et al. 1993a; Bubier et al. 1995). As a result, none of these small-scale measurement studies of wetland CH₄ emissions provide sufficient spatial information on the location and density of gas sampling chambers to assemble a reliable landscape-level (several kilometers squared) emission flux for wetland methane.

Consequently, the most practical method to validate the model’s predicted methane fluxes is by comparison to tower-based eddy flux measurements of landscape-scale CH₄ emissions. Several eddy correlation studies for methane flux have been published (Shurpali and Verma 1998; Verma and Billesbach 1998; Werner et al. 2003). For a first comparison of the model’s monthly predictions to measured CH₄ emission fluxes, data from the Bog Lake, Minnesota (47°32′N, 93°28′W), peatland (Shurpali and Verma 1998) confirm that the Ta term in Equation (2) above should be based on the simulated soil temperature from the CASA model rather than on monthly mean air temperature records for the location (Figure 1). Simulated soil temperature at approximately 20-cm depth results in higher CH₄ emission fluxes later into the growing season, which is consistent with both the timing and the magnitude of measured emission fluxes at this tower site. Methane emission fluxes from CASA model predictions based on monthly mean air temperature records peak too early in the growing season and fail to match the magnitude of measured CH₄ emission fluxes from July to October.

To expand upon these comparisons at the Bog Lake test site, we carried out a set of uncertainty analyses with the CASA wetland model, simulating carbon pools/fluxes driven by a combination of various input parameters (e.g., climate variables, plant and soil characteristics, and hydrological conditions) and determining impacts of varying parameter values on CH₄ emission fluxes. Input variables included air temperature and precipitation, available litter carbon from living plants, soil organic carbon content, and water table fluctuations. The model evaluation variables included predicted annual NPP, NEP, and methane flux. Error propagation from input parameters to output variables in the modeling procedure was examined, and uncertainties associated with the critical parameters were assessed. The results indicated that accuracy of air temperature data needs to be improved to reduce uncertainty in NPP predictions. Fluctuations of 2°C in the range of air temperature inputs can result in uncertainties as high as ±20% in
annual NPP predictions. CASA model predictions of soil microbial respiration were dependent on initial conditions of soil organic carbon content at this same level of ±20% for annual predictions. Accuracy of precipitation amounts that influence water table fluctuations were critical to NEP at the level of ±15%–20% for annual predictions, and therefore also to annual CH$_4$ flux predictions.

A second comparison of the model’s monthly predictions to measured CH$_4$ emission fluxes at the Park Falls, Wisconsin (45°56'N, 90°16'W), site (Werner et al. 2003) are also consistent with the timing of measured emission fluxes at this tall tower (Figure 2). The model’s tendency to exceed the measured CH$_4$ emission fluxes during the period of July to September is best explained by the mixed land cover types (forest and wetlands) in the tower footprint. The tower’s footprint is derived from a projection of both the upwind spatial extent and the relative weight
applied to upwind CH$_4$ sources and sinks (forest soils) contributing to the flux based on meteorological parameters. In contrast, the model is designed to simulate fluxes from a continuous cover type of inundated wetland vegetation as CH$_4$ sources. The inclusion of nonwetland forest area in the tower footprint thus depresses the aggregate methane observations compared to the modeled results for pure wetland.

Scaling of methane emission rates to the national level was accomplished using the Landsat-based National Land Cover Dataset (NLCD; http://landcover.usgs.gov/), which includes two wetland classes mapped at 30-m spatial resolution. NLCD wetland classes are defined as areas in which the soil or substrate is periodically saturated with or covered with water. “Woody wetlands” are areas where forest or shrubland vegetation accounts for 25%–100% of the land cover, whereas “emergent herbaceous wetlands” are areas where perennial herbaceous vegetation accounts for 75%–100% of the land cover.

NLCD mapping has been conducted for each of 10 geographic regions using early 1990s Landsat Thematic Mapper (TM) imagery augmented by ancillary geospatial datasets (e.g., census, slope/aspect/elevation, etc.). Briefly, the NLCD was compiled through unsupervised clustering (Kelly and White 1993) of Landsat TM data. The resulting spectral clusters were resolved into 1 of 21 thematic classes using logical modeling. Accuracy of the NLCD map classes has been assessed within primary sampling units (PSUs) defined by nonoverlapping, interior regions of aerial photographs circa 1990 acquired by the National Aerial Photograph Program (NAPP). A single PSU was randomly selected from each grid cell, with
all PSUs having an equal probability of being selected. The pixels selected within the first-stage PSUs were then stratified by mapped land cover class, and a simple random sample of pixels was selected independently for each land cover class.

For each NLCD mapping region, formulas were applied to estimate the overall and class-specific user’s accuracy (Story and Congalton 1986). High accuracy results (0.5–0.8) were reported for wetlands mapping in most regions of the country. The exceptions were regions 8 and 9 (California, Nevada, Arizona, and the Rocky Mountain states), where our own comparisons with the National Wetlands Inventory (Dahl 2000) suggest that the predominance of human-engineered canals, bypasses, and reservoirs contributes heavily to the low-accuracy values for the NLCD wetlands classification. In any case, our CASA model was not designed to operate in these human-engineered hydrologic zones where the growth of native wetland vegetation is largely excluded. Therefore, the omission of these canals, bypasses, and reservoirs in the NLCD wetland areas totals in regions 8 and 9 should not substantially affect the magnitude of national or statewide methane emission predictions for natural wetlands.

To compute the total CH$_4$ emission flux per 8-km grid cell, we summed the number of 30 m × 30 m wetland pixels identified in the NLCD within each 8-km grid cell and multiplied that sum by 900 (m$^2$ per 30 m × 30 m pixel). This total wetland coverage was used to scale-up the predicted monthly CH$_4$ emission flux to the area of an entire 8-km grid cell. We note it was not possible to include Alaska in the study at this time, chiefly because the wetlands mapping for that state has not been included (yet) in the NLDC, which we require for spatial upscaling.

The CASA model’s predicted mean emission flux of methane from wetlands of the continental United States totaled 5.5 Tg CH$_4$ per year (Figure 3), which converts to 126 Tg CO$_2$ equivalent (Energy Information Administration 2004; based on an estimated global warming potential factor of 23 for methane). This is less than 4% of the estimated global emission flux of CH$_4$ from natural wetlands of 145 ± 40 Tg per year (Lelieveld et al. 1998; Houweling et al. 1999) but is equivalent to 20% of anthropogenic methane emissions in the United States (mainly from landfills, natural gas systems, coal mines, mobile sources, ruminant animals, and rice cultivation), which totaled 26.2 Tg CH$_4$ per year (602 Tg CO$_2$ equivalent) in 2003 (Energy Information Administration 2004).

Ranked in terms of total annual flux, the 10 states with the highest predicted emissions (not considering Alaska) are all located in the Great Lakes region and the southern coastal United States (Table 1). Eight of the 10 states with the highest predicted CH$_4$ emissions are dominated by woody wetlands in the NLCD classification. Louisiana and Texas are states with relatively high CH$_4$ emissions and a more even split of total wetland area between woody and herbaceous cover classes.

4. Discussion

Based on extensive literature searches, it appears that our gridded prediction of CH$_4$ emission from wetlands of the continental United States is the first such estimate that provides a nationwide inventory flux of methane from natural wetland ecosystems. Two previous global modeling studies for wetland methane by Cao et al. (Cao et al. 1996) and Walter et al. (Walter et al. 2001) did not differentiate the uniquely U.S. sources from the larger continental emissions for all of
North America. Moreover, both of these studies were based on the global wetland database from Matthews and Fung (Matthews and Fung 1987), which projected the area of natural wetlands in the continental United States at only 210,710 km$^2$, approximately one-half of the 416,830 km$^2$ (103 million acres) of wetlands mapped in the mid-1980s by the U.S. Fish and Wildlife survey (Dahl and Johnson 1991).

Like the modeling approach of Christensen et al. (Christensen et al. 1996), the methane emission equation described in this study is simple, but it is built upon robust relationships between net ecosystem carbon fluxes and soil methane emissions measured across many wetlands types in North America. While other modeling approaches (Cao et al. 1996; Potter 1997; Walter et al. 2001; Zhuang et al. 2004) have been built upon more detailed processes of plant–soil physical and biochemical controls on methane production and emission pathways, the capacity to upscale these models with high confidence to regional and global scales remains limited by lack of attribute data for wetland soil and plant composition.

Further refinements of remote sensing and ecosystem modeling methods are underway in order to improve the utility of the methane flux predictions presented in this study. Maps of wetland coverage changes from updated NLCD Landsat mapping activities will permit analyses of conversion of inundated areas to other land cover types, such as conversion to agriculture, drainage for forestry, and

![Figure 3. Map of predicted methane emission totals from wetlands of the continental United States. Modeled emission fluxes are summed over 12 months for each 8 km × 8 km grid cell area.](image-url)
conversion for urban/industrial land uses. Models like the one described in this study can be used to assess how wetland trace gas fluxes may be affected by climate change (Watson et al. 1996; Gedney et al. 2004). Increased decomposition rates under warmer temperatures, particularly if associated with drier conditions, may lead to large carbon losses to the atmosphere (Gorham 1995). Warmer temperatures alone may also lead to enhanced CH$_4$ emissions. Changes in regional hydrology caused by precipitation changes may cause loss or enhanced growth of wetlands locally. Simulation approaches can address all of these potential future changes in natural greenhouse gas emissions.

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