Contemporary and projected biogenic fluxes of methane and nitrous oxide in North American terrestrial ecosystems

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Accurately estimating biogenic methane (CH_4) and nitrous oxide (N_2O) fluxes in terrestrial ecosystems is critical for resolving global budgets of these greenhouse gases (GHGs) and continuing to mitigate climate warming. Here, we assess contemporary biogenic CH_4 and N_2O budgets and probable climate-change-related impacts on CH_4 and N_2O emissions in terrestrial North America. Multi-approach estimations show that, during 1990–2010, biogenic CH_4 emissions ranged from 0.159 to 0.502 petagrams of carbon dioxide (CO_2) equivalents per year (Pg CO_2eq yr^{-1}, where 1 Pg = 1×10^{15} g) and N_2O emissions ranged from 0.802 to 1.016 Pg CO_2eq yr^{-1}, which offset 47–166% of terrestrial CO_2 sequestration (0.915–2.040 Pg CO_2eq yr^{-1}, as indicated elsewhere in this Special Issue). According to two future climate scenarios, CH_4 and N_2O emissions are projected to continue increasing by 137–151% and 157–227%, respectively, by the end of this century, as compared with levels during 2000–2010. Strategies to mitigate climate change must account for non-CO_2 GHG emissions, given their substantial warming potentials.

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Methane (CH_4) and nitrous oxide (N_2O) are two important greenhouse gases (GHGs), the infrared absorption properties of which increase near-surface temperatures (Forster *et al.* 2007; Montzka *et al.* 2011). The atmospheric concentrations of CH_4 and N_2O have increased dramatically since the beginning of Industrial Revolution and now exceed their natural ranges, according to ice core records (IPCC 2007). Methane and N_2O are, respectively, 25 and 298 times more potent in radiative forcing than carbon dioxide (CO_2) at a 100-year time horizon (Forster *et al.* 2007), and the importance of their roles in influencing global climate has been increasingly recognized (Kort *et al.* 2008; Schulze *et al.* 2009; Montzka *et al.* 2011; Tian *et al.* 2011). Among all emission and uptake pathways, those within terrestrial ecosystems (both natural and managed) make large contributions to atmospheric CH_4 and N_2O concentrations (Bousquet *et al.* 2006; Denman *et al.* 2007; Schulze *et al.* 2009; Tian *et al.* 2010; Dlugokencky *et al.* 2011). However, as compared with CO_2-related research, less effort has been invested in examining the magnitude of and underlying mechanisms responsible for the net land–atmosphere exchanges of these two gases.

In a nutshell:

- Biogenic methane (CH_4) and nitrous oxide (N_2O) emissions from North American terrestrial ecosystems are estimated to offset 50–150% or more of terrestrial CO_2 uptake
- Projected climate change could substantially increase biogenic CH_4 and N_2O emissions from North American terrestrial ecosystems by the end of the 21st century
- Although multiple approaches have been applied, large discrepancies still exist in estimating biogenic CH_4 and N_2O emissions. Future research must identify the sources of these discrepancies

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Land–atmosphere CH_4 exchange is dependent on CH_4 production, oxidation, and transport from soil pore water to the atmosphere (Figure 1). Methane is produced from anaerobic decomposition of organic materials by methanogenic bacteria. Once produced, CH_4 can be released into the atmosphere through three pathways: diffusion of dissolved CH_4 along a concentration gradient, transport via vascular plants, or ebullition (emission in gas bubbles). Concurrently, CH_4 oxidation by methanotrophic bacteria will occur within and above soils during its production and transport (Bousquet *et al.* 2006). Many factors – including water table depth, substrate quality and quantity, soil pH, soil moisture, presence of permafrost, oxygen concentration, and ratio of methanogenic to methanotrophic bacteria – directly regulate CH_4 production and oxidation (Zhuang *et al.* 2004; Tian *et al.* 2010; Xu *et al.* 2010; Banger *et al.* 2012; Dijkstra *et al.* 2012).

Atmospheric N_2O accounts for about 6% of the current greenhouse effect (Forster *et al.* 2007). The observed increase in N_2O concentration is mostly attributed to the

reactive nitrogen (N) inputs due to escalated use of synthetic N fertilizer and animal manure, cropland expansion, and processes associated with fossil-fuel combustion and biomass burning. Nitrous oxide production in soils is predominantly biological and occurs via nitrification (the assimilatory oxidation of ammonium to nitrate [NO_3^-]) and denitrification (the dissimilatory reduction of NO_3^- to N gases under anaerobic conditions; Figure 1). The balance of these two processes depends on the prevailing environmental conditions, soil properties, microbial community composition, N availability, and soil aeration status (Cantarel *et al.* 2011; Dijkstra *et al.* 2012; Xu *et al.* 2012).

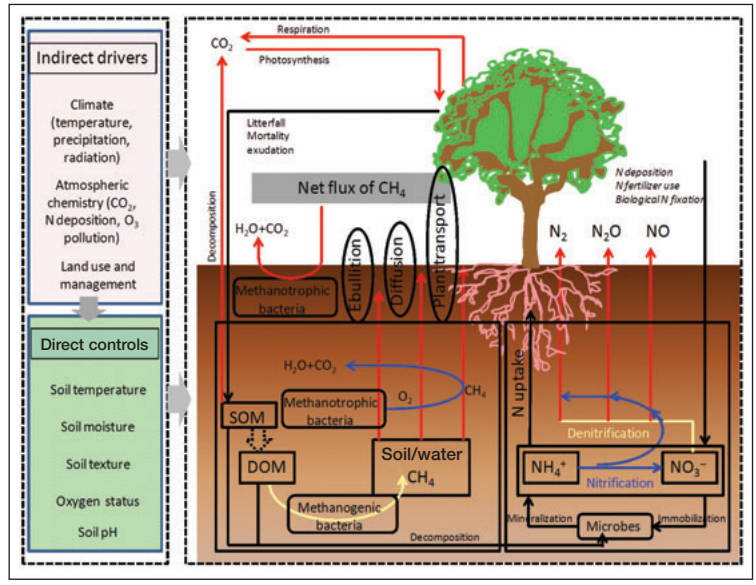

Figure 1. *Framework of key biological processes controlling terrestrial CH_4 and N_2O fluxes, including direct and indirect drivers. Red lines represent GHG exchange between terrestrial ecosystems and the atmosphere; yellow and blue lines indicate anaerobic and aerobic processes, respectively.*

Fluxes of CH_4 and N_2O in North America represent a large percentage of the global budgets of these gases (Kort *et al.* 2008; Tian *et al.* 2010). North America's natural wetlands, which are a major natural CH_4 source, account for ~20% of global wetland area (Zedler and Kercher 2005; Mitsch and Gosselink 2007). North America also has extensive areas of permafrost, which are sensitive to climate change and increased soil temperature. Previous studies indicate that future climate warming could greatly alter carbon (C) and nutrient dynamics in the permafrost region, resulting in large increases in CH_4 emissions (eg Zhuang *et al.* 2007; Koven *et al.* 2011). In addition, fossil-fuel combustion, N-fertilizer production, and cultivation-induced biological N fixation in North America account for ~23% of global anthropogenic N inputs (Galloway *et al.* 2004). Climate warming in high-latitude areas and increased N-fertilizer use in croplands are two important factors stimulating N_2O emissions on the continent (Mosier *et al.* 1998; Cantarel *et al.* 2011). Recent studies revealed that most of the terrestrial CO_2 sink in Europe and China has been offset by biogenic CH_4 and N_2O emissions (Schulze *et al.* 2009; Tian *et al.* 2011); however, to what extent this offset occurs in North America remains uncertain. Accurately estimating biogenic CH_4 and N_2O fluxes across the continent's terrestrial ecosystems is a critical step in resolving global budgets of these gases and developing climate-change mitigation strategies (Michalak *et al.* 2011; Montzka *et al.* 2011).

Four major approaches have been used to estimate the magnitude of biogenic CH_4 and N_2O fluxes in terrestrial ecosystems: (1) inventory, (2) empirical/statistical modeling, (3) atmospheric inverse modeling, and (4) process-based ecosystem modeling. Inventory reports generally follow methodologies recommended in the revised 1996 Intergovernmental Panel on Climate Change (IPCC) guidelines for national GHG inventories (IPCC/UNEP/OECD/IEA 1997) when calculating GHG emissions from each sector (eg agriculture or forestry; Mosier *et al.* 1998; USDA 2011); these inventories are typically conducted at national levels, focus on anthropogenic sources, and have large uncertainty ranges. Empirical/statistical models fit regression equations to relate GHG emissions to multiple environmental factors, such as temperature, soil moisture, and land-management practices (eg N input, residual burning, and livestock waste management; Xu *et al.* 2008; Bloom *et al.* 2010). This method simplifies the calculations of nonlinear responses of GHG dynamics to environmental changes and therefore limits our understanding of the key processes controlling GHG production and consumption. Inversion techniques use atmospheric observations in concert with a transport model to estimate GHG fluxes (Hirsh *et al.* 2006; Kort *et al.* 2008, 2010). Given the sparse observations and coarse spatial resolution (~1000 km^2) associated with this method, inversion-derived estimates are relatively uncertain. In addition, it is difficult to distinguish between natural and anthropogenic sources of GHG emissions from inversion constraints. Finally, process-based ecosystem models – such as DAYCENT (a daily version of the CENTURY model; Del Grosso *et al.* 2006), DLEM (Dynamic Land Ecosystem Model; Tian *et al.* 2010), DNDC (DeNitrification DeComposition; Li *et al.* 1996), and TEM (Terrestrial Ecosystem Model; Zhuang *et al.* 2007) – take into account critical biogeochemical processes (including CH_4 production and oxidation, nitrification, and denitrification) that control biogenic CH_4 and N_2O fluxes in terrestrial ecosystems. These models have been widely used to quantify the magnitudes of GHG fluxes and highlight spatio–temporal variations of fluxes in several ecosystems, including croplands, wetlands, grasslands, and forests, at spatial scales ranging from site, regional, and national to continental and global (Li *et al.* 1996; Mummey *et al.* 1998; Del Grosso *et al.* 2006; Potter *et al.* 2006; Melillo *et al.* 2009; Tian *et al.* 2010, 2011; Xu

et al. 2010, 2012). However, the accuracy of the models' estimations primarily relies on the accuracy of their spatially explicit input datasets and their representations of major biogeochemical mechanisms.

Here, we compile country-scale estimates of net CH_4 and N_2O fluxes in major ecosystem types from different studies and provide our best estimates of contemporary budgets of biogenic CH_4 and N_2O in North American terrestrial ecosystems. We then used the DLEM – a coupled biogeochemical model that simultaneously simulates exchanges of three GHGs (CO_2, CH_4, and N_2O) between terrestrial ecosystems and the atmosphere (Tian *et al.* 2010, 2011, 2012; Ren *et al.* 2011; Lu *et al.* 2012) – to predict possible CH_4 and N_2O fluxes from 2011 to 2099, under two distinct future climate-change scenarios. We assume anthropogenic drivers such as land-use change and agricultural management practices will remain constant (at 2010 levels), although future changes in such drivers may greatly affect CH_4 and N_2O fluxes. Finally, we discuss uncertainties and future research needs regarding estimations of biogenic CH_4 and N_2O budgets, using global warming potential to indicate the contribution of biogenic CH_4 and N_2O fluxes to global radiative forcing in CO_2 equivalents (CO_2eq).

Contemporary biogenic CH_4 and N_2O fluxes in terrestrial North America

Over the past decades, numerous studies have been conducted to quantify variations in fluxes of biogenic CH_4 and N_2O in North American terrestrial ecosystems (eg Li *et al.* 1996; Mummey *et al.* 1998; Smith *et al.* 2004; Zhuang *et al.* 2004, 2007; Del Grosso *et al.* 2006; Potter *et al.* 2006; Kort *et al.* 2008, 2010; Tian *et al.* 2010; Xu *et al.* 2010, 2012; Pickett-Heaps *et al.* 2011). However, most of these studies focused on (1) either CH_4 or N_2O and (2) either a specific biome type or a portion of North America. For example, multiple approaches have been used to estimate wetland CH_4 emissions (eg Zhuang *et al.* 2004; Potter *et al.* 2006) and cropland N_2O emissions (Li *et al.* 1996; Del Grosso *et al.* 2006). By bringing together estimates from different approaches, we are able to calculate the approximate ranges of CH_4 and N_2O budgets with relative accuracy.

Table 1. CH_4 fluxes estimated by multiple approaches for three North American countries during 1990–2010

		*SOCCR**	*DLEM**	*CASA**	*TEM**	*US EPA**
CH_4 source (Pg CO_2eq yr^{-1})						
Wetland	Alaska	0.042	0.073 (0.07†)		0.081 (0.078†)	
	Continental US	0.076	0.21	0.14		
	Canada	0.11	0.268 (0.24†)		0.156 (0.14†)	
	Mexico	0.005	0.016			
Rice paddy	US	0.008				0.007
	Canada	0				
	Mexico	0.0004				
North America				***0.240 ~ 0.583***		
CH_4 sink (Pg CO_2eq yr^{-1})						
Other biomes	US			–0.03¶		
	Canada			–0.027 ¶		
	Mexico			–0.024 ¶		
North America				***–0.081***		
Net CH_4 emissions (Pg CO_2eq yr^{-1})						
	US			0.095 ~ 0.269		
	Canada			0.083 ~ 0.241		
	Mexico			–0.0186 ~ –0.0076		
North America				***0.159 – 0.502***		

Notes: *Estimate sources: SOCCR (CCSP 2007); DLEM (Tian *et al.* 2010); CASA (Potter *et al.* 2006); TEM (Canada: Zhuang *et al.* 2004; Alaska: Zhuang *et al.* 2007); US EPA (2011). †Values in parentheses are original estimates for CH_4 emissions from terrestrial ecosystems. For Alaska, we modified these values to wetland emissions by assuming wetlands contributed 104% of the total terrestrial CH_4 emissions as simulated by DLEM; for Canada, this ratio was 111% in the DLEM simulation. ¶DLEM's estimates for other biomes are average values during 1990–2010.

Net exchange of CH_4 between terrestrial ecosystems and the atmosphere

Estimations of terrestrial CH_4 fluxes have exhibited wide variations. Mean annual CH_4 emissions from natural wetlands in North America during 1990–2010 were estimated to be 0.57 petagrams of CO_2eq per year (Pg CO_2eq yr^{-1}, where 1 Pg = 1×10^{15} g) by the DLEM (Table 1). But a lower estimation (0.24 Pg CO_2eq yr^{-1}, circa 2003) was reported in the first State of the Carbon Cycle Report (SOCCR), one of the US Climate Change Science Program's synthesis and assessment products (CCSP 2007). For the continental US, the SOCCR estimated a CH_4 source of 0.076 Pg CO_2eq yr^{-1} from natural wetlands, whereas process-based models reported higher CH_4 emissions: 0.14 Pg CO_2eq yr^{-1} by the Carnegie–Ames–Stanford Approach (CASA) model (Zhuang *et al.* 2004; Potter *et al.* 2006) and 0.21 Pg CO_2eq yr^{-1} by the DLEM (Tian *et al.* 2010). Wetland area delineation may partly explain the divergence between the two model estimates. For example, wetland area calculated from the Landsat-

based national land-cover dataset (Potter *et al.* 2006) was 26% lower than that used in both the DLEM simulation and the SOCCR report (43 million hectares [ha]), which was close to the wetland area estimate from US wetland inventory data (Dahl 1990). However, when considering CH_4 flux per unit wetland area, the SOCCR estimate was much lower than those from CASA and DLEM. The DLEM estimation (7.9–10.0 g CH_4–C m^{-2} yr^{-1}; Tian *et al.* 2010), was close to the lower end of the reported ranges from field observations (6.1–24.1 g CH_4–C m^{-2} yr^{-1} by Bridgham *et al.* [2006] and 13.1–37.0 g CH_4–C m^{-2} yr^{-1} by Barlett and Harriss 1993).

Wetland CH_4 emissions in Alaska were estimated to be 0.042 Pg CO_2eq yr^{-1} by the SOCCR, but process-based models generated larger biogenic CH_4 sources equivalent to 0.070 Pg CO_2eq yr^{-1} (DLEM) and 0.078 Pg CO_2eq yr^{-1} (TEM), even with the inclusion of CH_4 uptake by upland ecosystems (Zhuang *et al.* 2007; Tian *et al.* 2010). If upland ecosystem CH_4 uptakes are excluded (as simulated by the DLEM), DLEM and TEM estimates for wetland CH_4 emissions increase to 0.073 and 0.081 Pg CO_2eq yr^{-1}, respectively. Estimates for wetland CH_4 emissions from Alaska and the conterminous US could range from 0.118 to 0.291 Pg CO_2eq yr^{-1}, with more than one-third of those emissions being from Alaska. The SOCCR reported a CH_4 emissions estimate of 0.11 Pg CO_2eq yr^{-1} from natural wetlands in Canada; this was close to the TEM's estimate (0.14 Pg CO_2eq yr^{-1}) but lower than the DLEM's estimate (0.241 Pg CO_2eq yr^{-1}; Table 1), even though a small CH_4 sink from upland ecosystems was included in the TEM results. If the DLEM-estimated CH_4 uptake by upland ecosystems is excluded, TEM- and DLEM-simulated CH_4 emissions from wetlands were 0.156 and 0.268 Pg CO_2eq yr^{-1}, respectively. For wetlands in Mexico, both the SOCCR and DLEM reported smaller CH_4 sources of 0.005 and 0.016 Pg CO_2eq yr^{-1}, respectively, compared with those in Canada and the US.

In summary, the inventory and ecosystem modeling estimations for CH_4 emissions from natural wetlands in North America ranged from 0.233 to 0.575 Pg CO_2eq yr^{-1} for the time period 1990–2010, contributing 4–23% to global wetland emissions (2.5–5.8 Pg CO_2eq yr^{-1}; Denman *et al.* 2007). The inverse modeling results from National Oceanic and Atmospheric Administration's (NOAA) Carbon Tracker (www.esrl.noaa.gov/gmd/ccgg/carbontracker/index.html) also indicated that CH_4 emissions from natural ecosystems in North America were 0.337 ± 0.027 Pg CO_2eq yr^{-1} during 2000–2009 (Bruhwiler unpublished data). In addition to natural wetlands, rice paddy fields were another important terrestrial CH_4 source. The SOCCR estimated CH_4 emissions of 0.0004 and 0.008 Pg CO_2eq yr^{-1} from rice production in Mexico and the US, respectively. However, the SOCCR does not mention whether livestock and manure application were considered when estimating CH_4 flux from rice paddies. We used the DLEM simulation results to estimate CH_4 fluxes in upland ecosystems across North America because there was no other large-scale estimate available. All upland ecosystems acted as CH_4 sinks at a rate of 0.03, 0.027, and 0.024 Pg CO_2eq yr^{-1} in the US, Canada, and Mexico, respectively (Tian *et al.* 2010). Simulated results show that CH_4 emissions increased more in large, high-latitude areas than in other regions during 1979–2010 (Tian *et al.* 2010; Xu *et al.* 2010). Methane emissions in Canada showed a substantially increasing trend, whereas those in the US and Mexico did not appear to have changed much over the past three decades.

Overall, net CH_4 fluxes ranged from 0.096 to 0.269 Pg CO_2eq yr^{-1} for the US, 0.083 to 0.241 Pg CO_2eq yr^{-1} for Canada, and –0.0186 to –0.0076 Pg CO_2eq yr^{-1} for Mexico. For all of North America, estimates of net CH_4 exchange between terrestrial ecosystems and the atmosphere showed large uncertainty, with average emissions rates ranging from 0.159 to 0.502 Pg CO_2eq yr^{-1} over the past two decades.

Net N_2O exchange between terrestrial ecosystems and the atmosphere

Although some previous studies have estimated agricultural N_2O emissions in the US, considerable uncertainty still exists (Table 2). By using a combination of the DAYCENT model and the Tier 1 IPCC method, the US Environmental Protection Agency (EPA) reported that direct N_2O emissions from US agricultural soils were

Table 2. Estimates of biogenic N_2O emissions (expressed in Pg CO_2eq yr^{-1}) from different approaches and for different North American ecosystems during 1990–2010

		DAYCENT/IPCC*	DLEM*	DNDC*	NGAS*
Agricultural soils	US	0.163†	0.166	0.234–0.367	0.162–0.210
	Canada		0.013	0.022	
	Mexico		0.044		
	North America		***0.219–0.433***		
Non-managed ecosystems§	US		0.318¶		
	Canada		0.128¶		
	Mexico		0.137¶		
	North America		***0.583***		
Total	US		0.48–0.685		
	Canada		0.141–0.15		
	Mexico		0.181		
	North America		***0.802–1.016***		

Notes: *Estimate sources: DAYCENT/IPCC (US EPA 2011); DLEM (Tian *et al.* 2010); DNDC (US: Li *et al.* 1996; Canada: Smith *et al.* 2004); NGAS (Mummey *et al.* 1998). †DAYCENT estimate for agricultural soils is the average N_2O emissions reported for 1990, 2000, and 2005–2009. §The DLEM simulation classified vegetated area into non-managed ecosystems (including natural plant communities) and agricultural land (including typical crop types and cropping systems). Effects of forest plantation or age structure on CH_4 and N_2O fluxes were excluded. Urban area was treated as impervious surface and grassland. ¶DLEM's estimates for non-managed ecosystems are average values during 1990–2010.

0.163 Pg CO_2eq yr^{-1} over the past two decades (US EPA 2011). For the same time period, the DLEM simulation showed a similar estimate of 0.166 Pg CO_2eq yr^{-1} if multiple environmental drivers (eg climate, atmospheric CO_2, tropospheric ozone [O_3], N deposition, and land conversion) and intensive agronomic management practices (eg rotation, harvest, N fertilizer use, and irrigation, etc) were incorporated into the biogeochemical model framework. This estimate fell within the range of 0.162–0.210 Pg CO_2eq yr^{-1} as reported by Mummey *et al.* (1998). However, the DNDC model provided an even higher estimate of 0.234–0.367 Pg CO_2eq yr^{-1} for low and high soil-C scenarios (Li *et al.* 1996). Direct N_2O emissions from agricultural soils ranged from 0.013 to 0.022 Pg CO_2eq yr^{-1} for Canada and were 0.044 Pg CO_2eq yr^{-1} for Mexico (Smith *et al.* 2004; Tian *et al.* 2010).

Overall, the direct N_2O emissions estimated from North American agricultural land (0.219–0.433 Pg CO_2eq yr^{-1}) accounted for 10–54% of the global agricultural N_2O emissions (0.796–2.248 Pg CO_2eq yr^{-1}) reported in the IPCC Fourth Assessment Report by Denman *et al.* (2007). Uncertainties in N_2O emissions estimates might be caused by different environmental drivers and/or model structures and parameters. For example, the DLEM-based estimate (Tian *et al.* 2010) did not include manure as an N input source. This may result in an underestimation of N_2O emissions, though manure-application-induced N_2O emissions could be small (eg estimated as 0.007–0.011 teragrams of N per year [Tg N yr^{-1}] by Li *et al.* [1996] and as 0.034 Tg N yr^{-1} in 2008 by the US Department of Agriculture [USDA 2011]; where 1 Tg = 1×10^{12} g). Additionally, the DLEM simulations excluded tillage effects, which would have resulted in underestimated N_2O emissions from agricultural soils (Li *et al.* 1996), whereas the DAYCENT and DNDC models ignored land conversion and the DNDC adopted constant N-fertilizer amounts (Li *et al.* 1996; US EPA 2011).

According to the DLEM-based estimate (Tian *et al.* 2010), non-managed ecosystems in North America played an important role (0.583 Pg CO_2eq yr^{-1}) in determining terrestrial N_2O budgets, as a result of the large spatial areas involved (Table 2). In sum, N_2O released from North American terrestrial ecosystems totaled up to 0.802–1.016 Pg CO_2eq yr^{-1}. The relatively small variation in N_2O emissions estimates as compared with that of CH_4 may be due to the lack of multi-source estimates for N_2O emissions from non-managed ecosystems. Tian *et al.* (2010) indicated that forests were the source of the highest biogenic N_2O emissions, accounting for ~32% of total N_2O emissions across North America, followed by cropland (29%), shrubland (13%), and grassland (11%). Other ecosystem types shared the remaining 15%. However, only a few studies focused on N_2O emissions from these ecosystems, especially at regional, continental, or global scales. Previous studies have indicated that N_2O emissions are sensitive to climate warming, increasing atmospheric CO_2, and N addition (Dijkstra *et al.* 2012); future research should therefore address N_2O fluxes from non-managed ecosystems.

The highest N_2O emissions were found in the "corn belt" of the upper US Midwest and in tropical/subtropical forests in the southern portion of North America (Del Grosso *et al.* 2006; Tian *et al.* 2010; US EPA 2011; Miller *et al.* 2012; Xu *et al.* 2012). From 1979 to 2010, owing to N-fertilizer uses, N_2O emissions increased even more in these two regions than in other regions. Some high-latitude areas (eg the northwestern Canada) were characterized by lower N_2O emissions but experienced faster increases primarily due to climate warming. Nitrous oxide emissions decreased in the northern and southern parts of Mexico and along the southeastern coast of the US.

Relative to the terrestrial CO_2 sink of 0.915–2.040 Pg CO_2eq yr^{-1} in North America, as reported by King *et al.* (2012), biogenic CH_4 and N_2O emissions have offset 47–166% of terrestrial CO_2 sequestration. It is clearly important to have a complete analysis of terrestrial ecosystem–climate feedbacks that includes dynamics of CO_2, CH_4, and N_2O, rather than CO_2 fluxes alone.

Potential impact of climate change on biogenic CH_4 and N_2O fluxes

To examine the potential impact of climate change on biogenic CH_4 and N_2O fluxes in terrestrial ecosystems of North America, we set up six simulations within the DLEM, forced by six sets of projected climate data (2 scenarios × 3 General Circulation Models [GCMs]) for the period 2011–2099. In these simulations, the remaining model input data (including atmospheric CO_2 concentration, N deposition, O_3 pollution, and land-use and land-management practices) were kept constant at 2010 levels. We adopted projected future climate data from three GCMs (CCSM3, UKMO–HadCM3, and GFDL–CM2.1) under two IPCC emissions scenarios (A2 and B1). Data were downloaded from the World Climate Research Programme's Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset (Meehl *et al.* 2007; www.engr.scu.edu/~emaurer/global_data). The A2 scenario is mainly characterized as a world of independently operating nations, continuously increasing population, and regionally oriented economic development, while the B1 scenario is characterized by rapid economic development, population rising to nine billion in 2050 and then declining, clean and resource efficient technologies, and an emphasis on global solutions to economic, social, and environmental stability (IPCC 2007). To keep our simulations for the projected period (2011–2099) consistent with the historical/contemporary period (1979–2010), we statistically downscaled the climate data projected by the three GCMs from a resolution of 0.5 degrees latitude/longitude to a resolution of 32 km × 32 km.

Temperature in North America will continue to increase throughout the 21st century under both the A2 and B1 emissions scenarios. The three aforementioned

GCMs predict increases in annual temperatures of 1.88°C (B1 scenario) to 2.52°C (A2 scenario) by the 2050s and 2.54°C (B1 scenario) to 5.28°C (A2 scenario) by the 2090s, relative to the average annual temperature from 1979 to 2010. Projected increases in annual precipitation (averaged over the three models) are between 6% (UKMO–HadCM3 under the B1 scenario) and 15% (CCSM3 under the A2 scenario) by the 2050s and between 10% (UKMO–HadCM3 under the B1 scenario) and 26% (CCSM3 under the A2 scenario) by the 2090s, with high interannual fluctuations and spatial heterogeneity.

The simulation results indicated that CH_4 emissions would reach up to 0.784 ± 0.135 Pg CO_2eq yr^{-1} during the 2090s (~151% of that in the 2000s) while N_2O emissions would amount to 1.911 ± 0.220 Pg CO_2eq yr^{-1} (~227% of that in the 2000s) under the A2 climate scenario. In contrast, the B1 climate scenario would lead to lower emissions of CH_4 and N_2O at rates of 0.713 ± 0.063 Pg CO_2eq yr^{-1} and 1.321 ± 0.131 Pg CO_2eq yr^{-1} (equivalent to 137% and 157% of the 2000s' level), respectively. Both CH_4 and N_2O emissions would greatly increase with future climate change, but both appear to stabilize after the 2060s under the B1 climate scenario and continue to increase under the A2 climate scenario, possibly as a result of A2's more rapid warming trend (Figure 2).

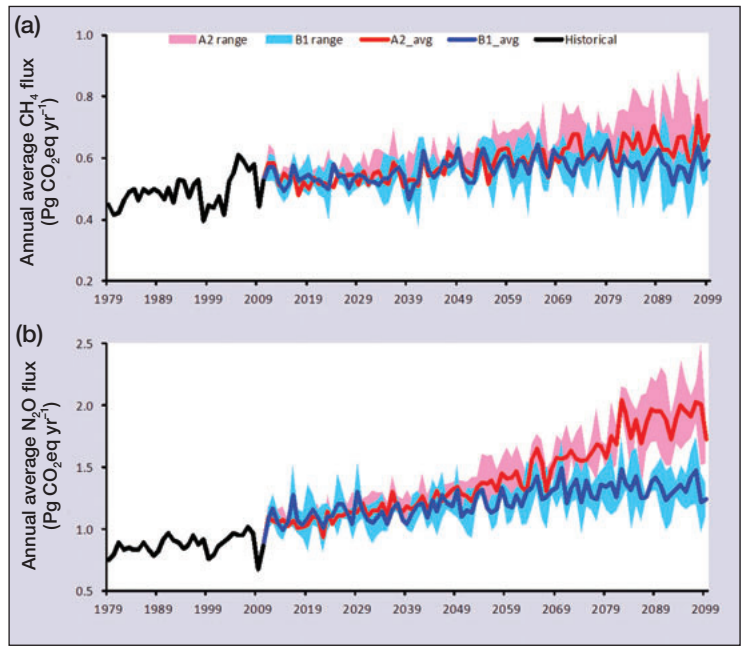

Figure 2. *Contemporary and projected mean annual CH_4 (a) and N_2O fluxes (b) in North American terrestrial ecosystems during 1979–2099 as estimated by the Dynamic Land Ecosystem Model (DLEM). Note that the future projection is driven by two climate scenarios from three GCM models. The pink and blue shaded areas are 95% confidence intervals of mean CH_4 and N_2O fluxes driven by the A2 and B1 scenarios, respectively.*

At the country scale, mean annual CH_4 emissions in Canada would increase by 195.9 and 123.8 Tg CO_2eq yr^{-1} under the A2 and B1 climate scenarios, respectively, by the end of this century. Canada would contribute the most to the increased North American CH_4 emissions (Figure 3). In contrast, CH_4 emissions would increase less rapidly (nearly 80 Tg CO_2eq yr^{-1}) in the US under both climate scenarios during 2011–2099. Methane uptake in Mexico would increase by 9.1 and 3.2 Tg CO_2eq yr^{-1} under the A2 and B1 climate scenarios, respectively, but the magnitude of increasing CH_4 uptake from Mexico would be far less than that of the increasing CH_4 emissions from Canada and the US. The high (A2) and low (B1) temperature scenarios would cause a greater difference in N_2O fluxes (as compared with CH_4 fluxes) in these different countries. The US would be the largest contributor to increased N_2O emissions in North America, with increases of 657.4 and 302.4 Tg CO_2eq yr^{-1} under the A2 and B1 scenarios, respectively. Nitrous oxide emissions in both Canada and Mexico would increase by ~200 Tg CO_2eq yr^{-1} under the A2 scenario and by less than 100 Tg CO_2eq yr^{-1} under the B1 scenario.

To better understand future changes in CH_4 and N_2O emissions in the US, we divided the country into seven regions: Alaska, Northwest, Southwest, Great Plains, Midwest, Northeast, and Southeast, according to Karl *et al.* (2009) (Figure 3). Our model simulations showed large regional variations in CH_4 and N_2O emissions responses to future climate change over the coming decades. Because of its extensive wetland area and high sensitivity to climate warming, Alaska would have the largest CH_4 emissions increase, ranging from 33.8 to 53.5 Tg CO_2eq yr^{-1} driven by low (B1) and high (A2) temperature scenarios. The Northeast is the second largest contributor to the CH_4 increase by 20.2 and 10.4 Tg CO_2eq yr^{-1} under A2 and B1 scenarios, respectively, followed by the Midwest. The largest increase in N_2O emissions, ranging from 135.0 to 264.1 Tg CO_2eq yr^{-1} during 2011–2099, would occur in the Great Plains as a result of high N availability from historical fertilizer inputs. The Midwest and Southeast would also be characterized by substantial N_2O emissions increases of >100 Tg CO_2eq yr^{-1} and ~50 Tg CO_2eq yr^{-1} under A2 and B1 scenarios, respectively. Partly because of their relatively limited areal extent, the Northwest and Northeast would be the smallest overall contributors to both CH_4 and N_2O increases in the future.

Uncertainty and future research needs

Although many studies have estimated the terrestrial budgets of CH_4 and N_2O through multiple approaches, large uncertainties still exist. This study has identified several major sources of uncertainty that need to be addressed. First, the descriptive wetland data that are currently available inherently bias the estimated CH_4 fluxes. A set of consistent, commonly accepted data is needed to

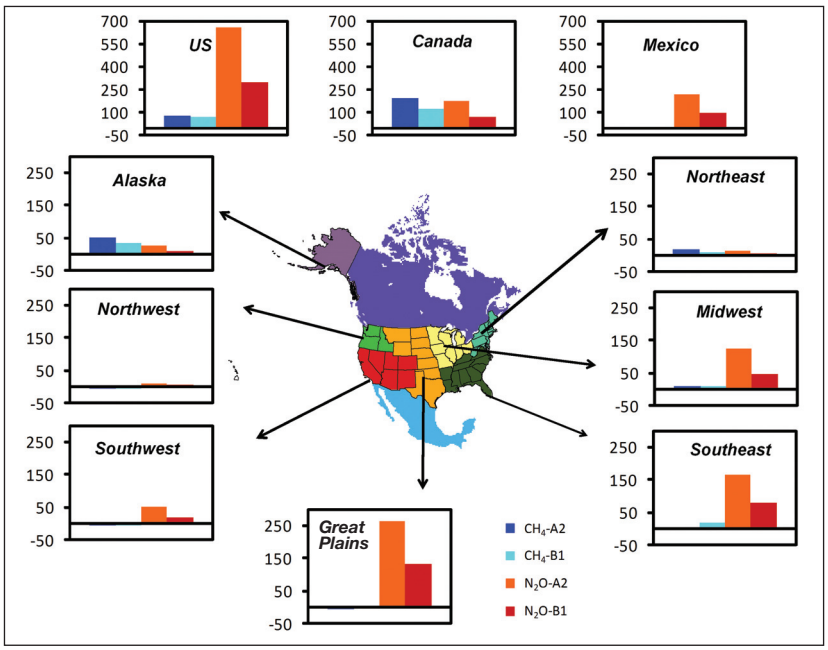

Figure 3. *Projected changes in CH_4 and N_2O emissions in response to A2 and B1 climate scenarios in the three countries of North America (upper panels) and seven regions of the US by the end of the 21st century as estimated by Dynamic Land Ecosystem Model (DLEM). The y-axes display CH_4 and N_2O emission change (expressed in Tg CO_2eq yr^{-1}).*

characterize the type, area, and distribution of wetlands given that this ecosystem is one of the largest contributors to divergences among reported estimates. Second, differences that contribute to uncertainty in modeling studies might also arise from input data with divergent spatial resolutions. Examples include 0.5 × 0.5 latitude/longitude degrees for TEM (Zhuang *et al.* 2004, 2007), 32 km × 32 km for DLEM (Tian *et al.* 2010), 8 km × 8 km for CASA (Potter *et al.* 2006), state-level in the US and soil-group level in Canada for DNDC (Li *et al.* 1996; Smith *et al.* 2004), and state- and sub-state level for DAYCENT (Del Grosso *et al.* 2006). Refining the critical input datasets would therefore help reconcile the estimates provided by different approaches. In addition, biogenic N_2O emissions from non-managed ecosystems at the continental scale are not well studied; future research should focus on N_2O fluxes from natural ecosystems.

The projected CH_4 and N_2O fluxes in response to future climate change remain far from certain for several reasons. First, we did not consider potential vegetation shifts, such as decreased wetland area due to future climate warming or drought in some areas (Avis *et al.* 2011) or the likely increase in drained wetland area due to cropland expansion and urbanization. Doing so would tend to overestimate CH_4 emissions or underestimate CH_4 uptake across North America. Therefore, the model representation of vegetation dynamics and ecosystem hydrology in response to future climate change needs to be incorporated to simulate changes in wetland area. Second, some underlying mechanisms should be better represented in ecosystem models. For example, freeze–thaw cycles would be an important factor for both CH_4 and N_2O fluxes but are often excluded from current research efforts. Inclusion of a permafrost C–climate feedback would greatly increase the accuracy of terrestrial CH_4 and N_2O flux estimates under future climate-change scenarios (Xu *et al.* 2010, 2012; Koven *et al.* 2011). Soil consumption of N_2O was also not included in this study, thereby likely leading to overestimates of N_2O emissions from North America. Third, in our projections, we only quantified the likely GHG patterns under future climate scenarios, but did not consider the contributions of other changing environmental factors, such as elevated atmospheric CO_2, N deposition, and land-use and land-management practices. Future climate scenarios should be related to different emissions scenarios, which would primarily affect atmospheric CO_2 concentration and N deposition. It is important to estimate projected biogenic CH_4 and N_2O fluxes within a multi-factor environmental change framework (Tian *et al.* 2011). Fourth, continental-scale estimates of projected biogenic CH_4 and N_2O budgets were primarily based on the DLEM simulations because no other suitable estimates were available. Clearly, data–model integration and model–model intercomparisons are needed to reduce uncertainties in estimating CH_4 and N_2O budgets.

Conclusion

This study provides the most up-to-date and comprehensive estimates of contemporary and projected biogenic CH_4 and N_2O fluxes in North American terrestrial ecosystems. Our results show that biogenic CH_4 and N_2O emissions likely offset 47–166% of terrestrial CO_2 sequestration in North America over the past two decades. Thus, non-CO_2 GHGs must be considered when assessing the role of terrestrial ecosystems in climate-change dynamics. Examining and modeling potential impacts of climate change on biogenic CH_4 and N_2O fluxes is therefore crucial for accurate climate-change assessment. Our projections with the DLEM indicate that biogenic CH_4 and N_2O emissions, solely driven by climate change, will continue to increase and be a major influence on warming in this century.

This study also provides information for identifying the potential hotspots of CH_4 and N_2O emissions in North America. For example, high-latitude regions could soon become a major hotspot for CH_4 emissions if climate warming continues as predicted. The conterminous US would be the largest contributor to increased N_2O emissions in North America, but Canada and Alaska would

experience a faster N_2O increase primarily as a result of climate warming.

To obtain more accurate estimates of North American biogenic CH_4 and N_2O budgets and to fully understand underlying flux mechanisms, we need a better understanding of critical biogeochemical processes as well as classification and distribution of key vegetation covers, including natural wetlands and inundation extents. Future projections of CH_4 and N_2O emissions should consider additional driving forces. In particular, anthropogenic drivers, including land-use change and land-management practices, need to be further investigated.

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