

Net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming

Hanqin Tian,^{1,2} Xiaofeng Xu,^{1,2} Chaoqun Lu,^{1,2} Mingliang Liu,^{1,2} Wei Ren,^{1,2} Guangsheng Chen,^{1,2} Jerry Melillo,³ and Jiyuan Liu⁴

Received 17 April 2010; revised 30 January 2011; accepted 10 February 2011; published 13 May 2011.

[1] China's terrestrial ecosystems have been recognized as an atmospheric CO₂ sink, however, it is uncertain whether this sink can alleviate global warming given the fluxes of CH₄ and N₂O. In this study, we used a process-based ecosystem model driven by multiple environmental factors to examine the net warming potential resulting from net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere during 1961–2005. In the past 45 years, China's terrestrial ecosystems were found to sequester CO₂ at a rate of 179.3 Tg C yr⁻¹ with a 95% confidence range of (62.0 Tg C yr⁻¹, 264.9 Tg C yr⁻¹) while emitting CH₄ and N₂O at rates of 8.3 Tg C yr⁻¹ with a 95% confidence range of (3.3 Tg C yr⁻¹, 12.4 Tg C yr⁻¹) and 0.6 Tg N yr⁻¹ with a 95% confidence range of (0.2 Tg N yr⁻¹, 1.1 Tg N yr⁻¹), respectively. When translated into global warming potential, it is highly possible that China's terrestrial ecosystems mitigated global climate warming at a rate of 96.9 Tg CO₂eq yr⁻¹ (1 Tg = 10¹² g), substantially varying from a source of 766.8 Tg CO₂eq yr⁻¹ in 1997 to a sink of 705.2 Tg CO₂eq yr⁻¹ in 2002. The southeast and northeast of China slightly contributed to global climate warming; while the northwest, north, and southwest of China imposed cooling effects on the climate system. Paddy land, followed by natural wetland and dry cropland, was the largest contributor to national warming potential; forest, followed by woodland and grassland, played the most significant role in alleviating climate warming. Our simulated results indicate that CH₄ and N₂O emissions offset approximately 84.8% of terrestrial CO₂ sink in China during 1961–2005. This study suggests that the relieving effects of China's terrestrial ecosystems on climate warming through sequestering CO₂ might be gradually offset by increasing N₂O emission, in combination with CH₄ emission.

Citation: Tian, H., X. Xu, C. Lu, M. Liu, W. Ren, G. Chen, J. Melillo, and J. Liu (2011), Net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming, *J. Geophys. Res.*, 116, G02011, doi:10.1029/2010JG001393.

1. Introduction

[2] The atmospheric concentrations of major greenhouse gases (GHGs: CO₂, CH₄ and N₂O) have increased significantly since the Industrial Revolution, and have been considered a major force of climate variability and changes [Forster *et al.*, 2007]. These three greenhouse gases in sum contribute to more than 90% of the anthropogenic climate

warming [Forster *et al.*, 2007; Rodhe, 1990]. A host of studies have highlighted land ecosystem for its capability in absorbing CO₂ released from fossil fuel combustion, and therefore mitigating potential atmospheric and climate changes [Baldocchi, 2008; Piao *et al.*, 2009; Schimel *et al.*, 2001; Wofsy *et al.*, 1993]. Despite the fact that the atmospheric concentrations of CH₄ and N₂O are much lower than that of ambient CO₂, CH₄ and N₂O highly affect the climate system with radiative efficiencies that are 25 and 298 times greater than CO₂ at a 100 year time horizon [Forster *et al.*, 2007; Rodhe, 1990]. Compared to intensive studies on terrestrial CO₂ flux [Baldocchi, 2008; Law *et al.*, 2002; Saleska *et al.*, 2003; Wofsy *et al.*, 1993], however, much less work has been done in quantifying the magnitude, spatial and temporal patterns of CH₄ and N₂O fluxes in the terrestrial ecosystems [Blais *et al.*, 2005; Repo *et al.*, 2009; Song *et al.*, 2009; Zou *et al.*, 2009].

[3] China has drawn much attention from both the public and the scientific community as it has surpassed the United

¹Ecosystem Dynamics and Global Ecology Laboratory, School of Forestry and Wildlife Sciences, Auburn University, Auburn, Alabama, USA.

²International Center for Climate and Global Change Research, Auburn University, Auburn, Alabama, USA.

³The Ecosystem Center, Marine Biological Laboratory, Woods Hole, Massachusetts, USA.

⁴Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China.

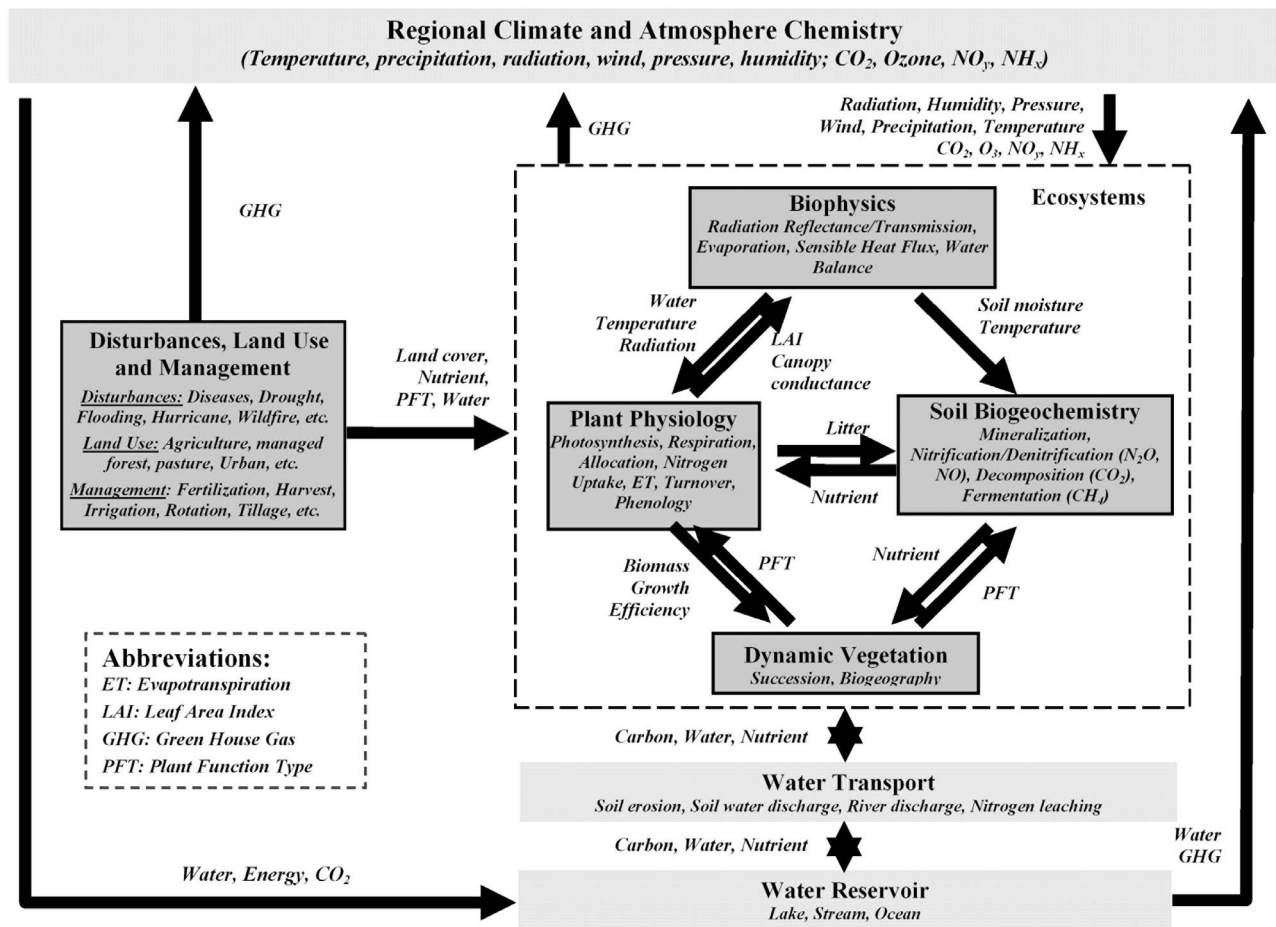


Figure 1. Framework showing the major components and their connections in the Dynamic Land Ecosystem Model (DLEM). (See auxiliary material for detailed information.)

States in 2006 as the largest emitter of CO₂ [Gregg *et al.*, 2008]. A number of studies have proved that China's terrestrial ecosystems have acted as a substantial carbon sink in recent decades [Fang *et al.*, 2007, 2001; Huang and Sun, 2006; Pan *et al.*, 2004; Piao *et al.*, 2009]; however, it remains uncertain whether the CO₂ sink can be translated into a mitigator for climate warming because the emissions of CH₄ and N₂O in China are relatively high [Chen *et al.*, 2000; Ding and Cai, 2007; Huang *et al.*, 2005, 1998, 2009; Yan *et al.*, 2003b; Zou *et al.*, 2010]. Thus, a comprehensive study which simultaneously examines the exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere is greatly needed [Li *et al.*, 2005; Qiu *et al.*, 2009].

[4] Although a great number of site-specific studies on CO₂, CH₄ and N₂O fluxes have been conducted in China for several decades, few simultaneously measured all three greenhouse gases [Song *et al.*, 2009; Tang *et al.*, 2006; Zou *et al.*, 2004]. At the regional scale, the spatial and temporal patterns of three biogenic GHG budgets in China remain uncertain [Qiu *et al.*, 2009]. At present, individual technique, with either top-down or bottom-up estimate, rarely spans spatial and temporal scales to produce regional, long-term GHG budgets; furthermore, among these methods, gaps in the coverage of greenhouse gas species, emission

sources and land ecosystem types, etc. might introduce large uncertainties to the integration of multiple approaches [Schulze *et al.*, 2009]. Process-based ecosystem models concurrently simulating CO₂, CH₄ and N₂O can be adopted as an alternative tool for investigating GHG fluxes on a regional level, as well as GHG contributions to climate change in terms of global warming potential (GWP). In this study, we used a highly integrated model, Dynamic Land Ecosystem Model (DLEM), to examine how China's terrestrial ecosystems contributed to the budgets of three GHGs during 1961–2005, and how net exchange of GHGs in terms of warming potential varied in both spatial and temporal contexts.

2. Materials and Methods

2.1. Model Description

[5] The DLEM model is a highly integrated process-based ecosystem model that aims at simulating the fluxes and storage of carbon, water and nitrogen among/within terrestrial ecosystem components while taking into consideration of multiple natural and anthropogenic perturbations. DLEM is composed of five major submodules focusing on biophysics, plant physiology, soil biogeochemistry, vegetation dynamics, land use and management as well as disturbances such as hurricane, fire, insect, etc. (Figure 1). The

fully coupled plant-soil-atmosphere continuum in model framework covers the major processes controlling uptake and release of CO₂, CH₄ and N₂O by terrestrial ecosystems. Meanwhile, the concurrent impacts of changes in climate, atmospheric composition, and land use and management practices are integrated into DLEM to retrieve reliable historical evolution and spatial patterns of the biogenic GHG budgets. DLEM has been widely applied to a variety of terrestrial ecosystem types across the globe and the detailed assumptions and processes are well documented in our previous work [Chen *et al.*, 2006; Liu *et al.*, 2008; Lu, 2009; Ren *et al.*, 2007, 2011a, 2011b; Tian *et al.*, 2008, 2010a, 2010b, 2011; Xu *et al.*, 2010; Zhang *et al.*, 2007].

[6] In the DLEM model, the carbon balance of vegetation depends on carbon exchanges from photosynthesis, autotrophic respiration, and litterfall, as well as plant mortality [Tian *et al.*, 2005, 2008, 2010b]. Plants assimilate carbon via photosynthesis, and utilize portions of the absorbed carbon to compensate for the carbon loss through maintenance/growth respiration, tissue turnover, and reproduction. Net ecosystem exchange is the balance of net primary production (NPP), ecosystem heterotrophic respiration and methane flux. The NPP is the difference between gross primary production and autotrophic respiration, which have been described by Tian *et al.* [2010a].

[7] The methane module in the DLEM model mainly simulates the production, consumption, and transport of CH₄ [Tian *et al.*, 2010a]. Due to relatively small contribution from other substrates [Conrad, 1996; Mer and Roger, 2001], DLEM only considers the CH₄ production from dissolved organic carbon (DOC), which is indirectly controlled by environmental factors including soil pH, temperature and soil moisture content. The DOC was produced through three pathways, GPP allocation, and decomposition byproducts from soil organic matter and litterfall. CH₄ oxidation, including the oxidation during CH₄ transport to the atmosphere, CH₄ oxidation in the soil/water, and atmospheric CH₄ oxidation on the soil surface, is determined by CH₄ concentrations in the air or soil/water, as well as soil moisture, pH, and temperature. Most CH₄-related biogeochemical reactions in the DLEM were described as the Michaelis-Menten equation with two coefficients: maximum reaction rate and half-saturated coefficient. Three pathways for CH₄ transport from soil to the atmosphere, ebullition, diffusion, and plant-mediated transport, are considered in the DLEM [Tian *et al.*, 2010a].

[8] In the DLEM, both denitrification and nitrification processes are simulated as one-step processes as we do not consider the midproducts in each process. Nitrification, a process converting ammonium into nitrate, is simulated as a function of soil temperature, moisture, and the NH₄⁺ concentration [Lin *et al.*, 2000]. Denitrification, through which the nitrate is converted into N gases, is simulated in the DLEM as a function of soil temperature, moisture, and the NO₃⁻ concentration [Lin *et al.*, 2000]. All the products of nitrification and denitrification that leave the system are N-containing gases. The empirical equation reported by Davidson *et al.* [2000] is used to separate N₂O from other gases (mainly NO and N₂).

[9] The simulated exchanges of carbon, water and nitrogen between the interfaces at both site and regional levels have been well calibrated and extensively validated against field

observation and inventory results (see Text S1, available as auxiliary material).¹ Especially for the three biogenic GHG budgets, simulation experiments conducted in North America and China found that DLEM performed well in capturing both the interannual/seasonal and spatial patterns of CO₂, CH₄ and N₂O fluxes [Ren *et al.*, 2007, 2011a, 2011b; Tian *et al.*, 2010a, 2010b, 2011; Zhang *et al.*, 2007]. More detailed information concerning CH₄ and N₂O production and emission can be referred to our other publications [Tian *et al.*, 2010a, 2010b; Xu, 2010; Xu *et al.*, 2010].

2.2. Input Data

[10] A series of spatially and/or temporally explicit data sets have been developed to characterize multiple driving forces for the DLEM model such as changes in climate (temperature, precipitation, shortwave radiation and humidity) [Chen *et al.*, 2006], atmospheric composition (CO₂, O₃ and N deposition) [Lu, 2009; Lu and Tian, 2007; Ren *et al.*, 2007], and land use and management practices (fertilization, irrigation, harvest, etc.) [Liu and Tian, 2010; Liu *et al.*, 2008] at a spatial resolution of 10 km × 10 km with a time step ranging from daily to yearly. The atmospheric CO₂ concentration data from 1900 to 2005 was obtained from the Carbon Dioxide Information Analysis Center (CDIAC, <http://cdiac.ornl.gov/>). The soil depth, pH, and texture maps were generated from the 1:1 million soil maps (Institute of Soil Science, Chinese Academy of Sciences) and the second national soil survey of China (National Soil Survey Office).

[11] During 1961–2005, China's terrestrial ecosystems experienced substantial environmental changes, such as land conversion, climate change, shifts in atmospheric composition including atmospheric CO₂ concentration, ozone pollution, and nitrogen deposition (Figure 2). The atmospheric CO₂ concentration increased from 317 ppm in 1961 to 380 ppm in 2005, but we assumed that the atmospheric CO₂ concentration is spatially homogeneous across China. All the other environmental factors showed significant changing rates over time and space. We divided China into five regions: northwest, north, northeast, southwest, and southeast. The maximum, minimum, and average temperature showed a significantly increasing rate at regional and national scales; the national increasing rates are $0.29 \pm 0.03^\circ\text{C} (10\text{a})^{-1}$, $0.23 \pm 0.04^\circ\text{C} (10\text{a})^{-1}$, $0.38 \pm 0.03^\circ\text{C} (10\text{a})^{-1}$ for average, maximum, and minimum temperature, respectively. All the temperature changes are statistically significant for five regions. However, significance levels of precipitation change are varied among regions. Precipitation amount in the northwestern China significantly increased by $11.20 \pm 3.23 \text{ mm} (10\text{a})^{-1}$, and marginally significant increase of $28.04 \pm 16.31 \text{ mm} (10\text{a})^{-1}$ was found in the southeastern China, while no significantly changing rate was observed for other regions; at national scale, precipitation showed a significantly increasing rate at $9.68 \pm 4.06 \text{ mm} (10\text{a})^{-1}$ [Tian *et al.*, 2011].

[12] The mean monthly accumulated atmospheric ozone concentration above a threshold of 40 ppbv (AOT40) throughout the nation was increased from 100 ppb h in 1961 to 3600 ppb h in 2005, with a significantly increasing rate at $72.49 \pm 3.06 \text{ ppb h yr}^{-1}$. The severity of ozone pollution largely varied over space and time. The increase accelerated

¹Auxiliary materials are available in the HTML. doi:10.1029/2010JG001393.

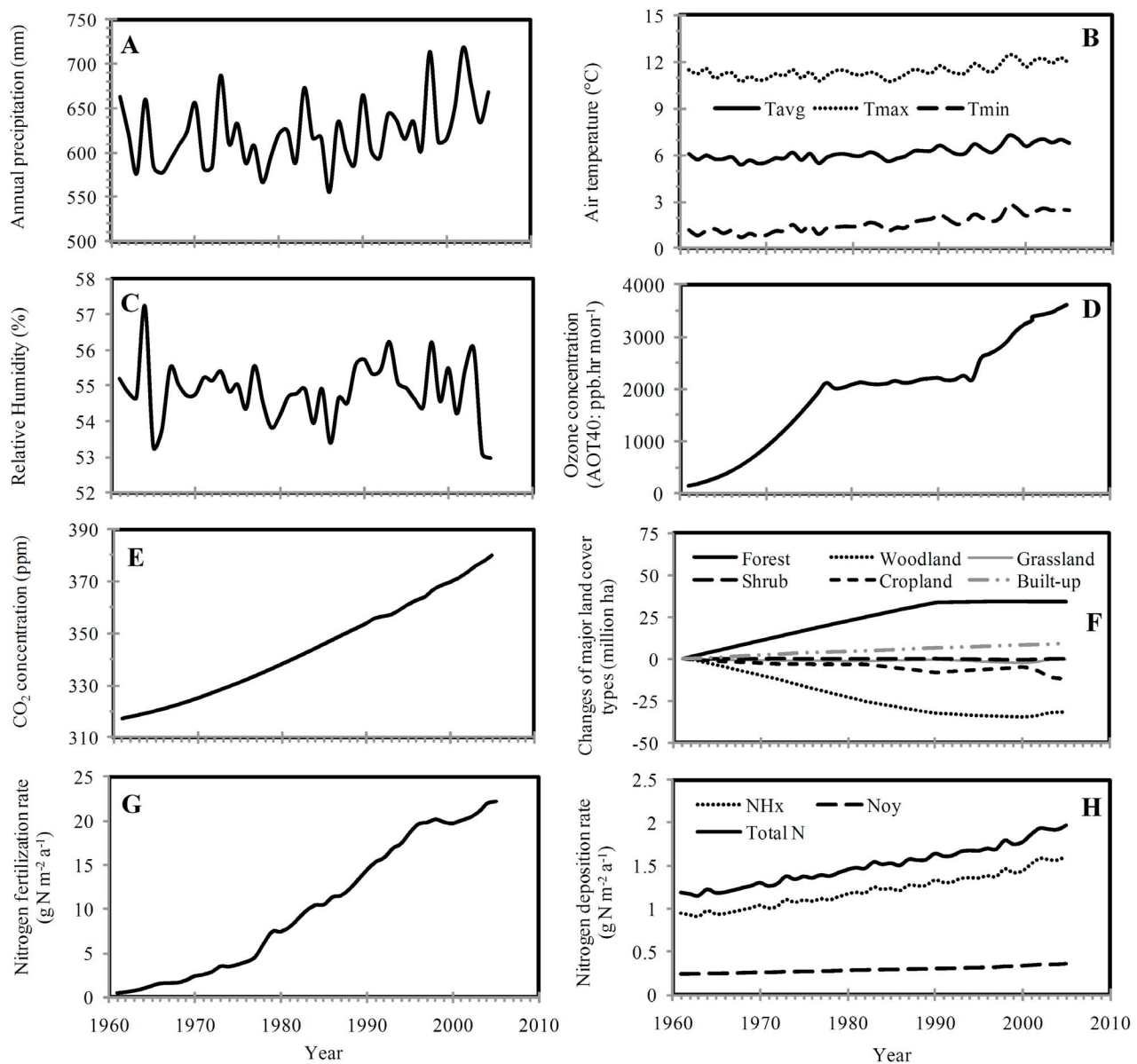


Figure 2. Temporal variation of (a) mean annual precipitation (mm), (b) maximum, minimum, and average temperature (°C), (c) relative humidity (%), (d) ozone pollution (AOT: ppb h month⁻¹), (e) atmospheric CO₂ concentration (ppm), (f) areal changes of major biome (million ha), (g) nitrogen fertilizer application rate (g N m⁻² yr⁻¹), and (h) nitrogen deposition rate (g N m⁻² yr⁻¹) along the study period.

since the early 1990s, possibly due to rapid urbanization during that period in China [Liu *et al.*, 2005a, 2005b]; over the study period, a significantly increasing rate of ozone pollution was observed for all five regions. Severe ozone pollution was observed in western and northern China, whereas southeastern and northeastern China was exposed to low-level ozone concentration (Figure 3b).

[13] The nitrogen deposition rate increased from 1.19 g N m⁻² yr⁻¹ in 1961 to 1.96 g N m⁻² yr⁻¹ in 2005, annually increasing by 16.72 ± 0.42 mg N m⁻² yr⁻¹. The increasing rate of nitrogen deposition showed substantial spatial variation, with the highest annual increasing rate of 42.81 ± 1.24 mg N m⁻² yr⁻¹ in southeastern China and the lowest rate of 6.21 ± 0.34 mg N m⁻² yr⁻¹ in northwestern

China. The rapidest increases of both NO_y-N and NH_x-N deposition rates occurred in central and southeastern China, especially in the Yangtze River Basin, due to higher fossil fuel combustion for industrial development, N fertilizer application in cropland and winter heating [Lu and Tian, 2007]. In recent years, nitrogen deposition rates could have reached more than 4 g N m⁻² yr⁻¹ in recent years in southeastern China (e.g., wet deposition of 5.08 g N m⁻² yr⁻¹ in Hangzhou as measured by Shui *et al.* [1999]; wet deposition of 4.46 g N m⁻² yr⁻¹ in Dabagou and 5.63 g N m⁻² yr⁻¹ in Jinyunshan measured by EANET, 2001, <http://www.eanet.cc/>).

[14] The spatial and temporal patterns of nitrogen fertilizer application rate largely varied across China. The annual mean nitrogen fertilizer application increased from 0.42 g N m⁻²

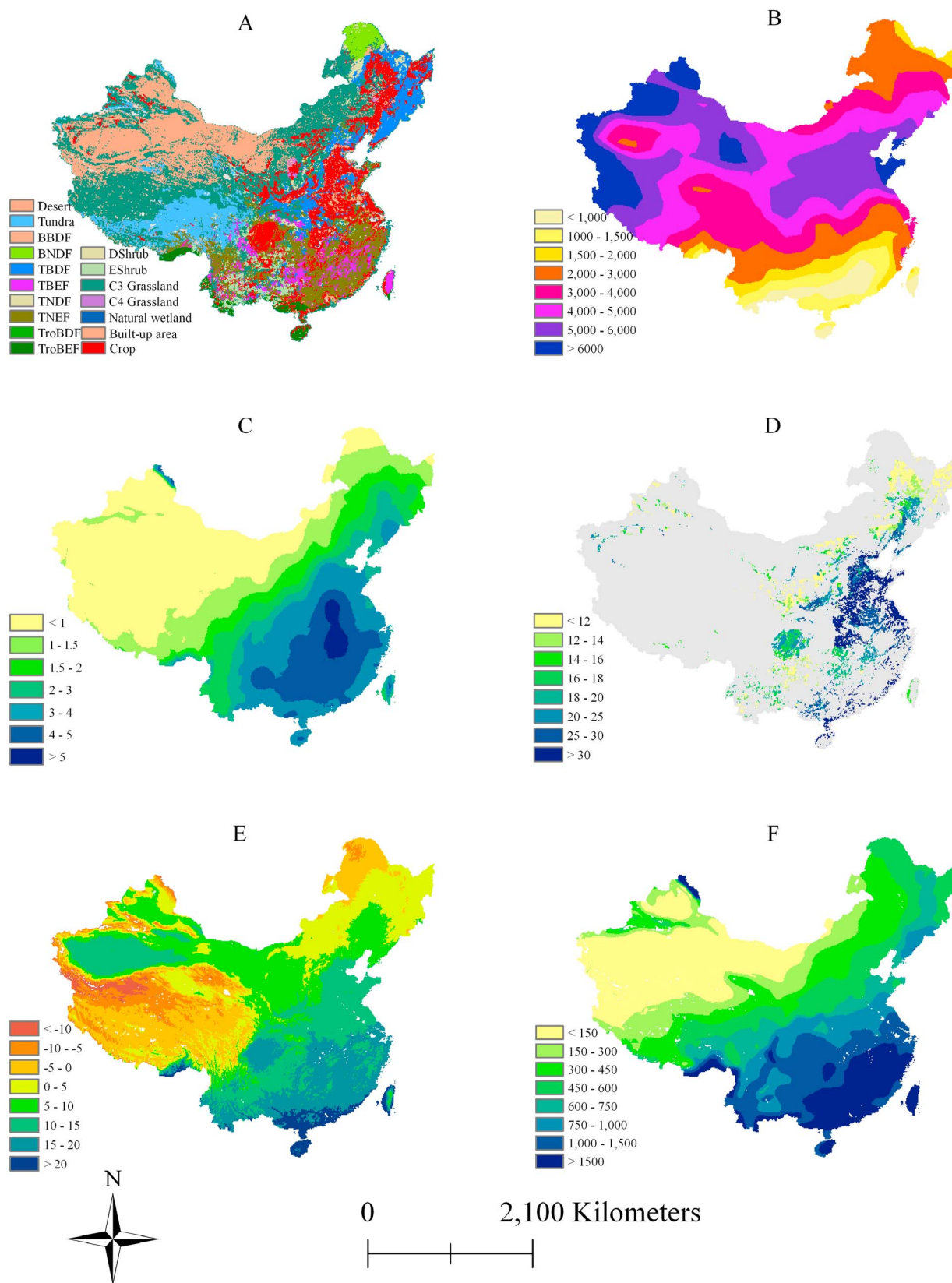


Figure 3. Spatial distribution of (a) contemporary vegetation, (b) ozone pollution (AOT: ppb h month⁻¹), (c) nitrogen deposition (g N m⁻² yr⁻¹), (d) nitrogen fertilizer application rate (g N m⁻² yr⁻¹), (e) daily air temperature (°C), and (f) mean annual precipitation (mm). (Figures 3a–3d show the data in the year of 2005, and Figures 3e and 3f show the 45 year average air temperature and precipitation.)

yr⁻¹ in 1961 to 22.23 g N m⁻² yr⁻¹ in 2005 with an overall annual increasing rate of 0.57 ± 0.01 g N m⁻² yr⁻¹ (Figure 2). The highest fertilization rates appeared in southeastern and northern China (Figure 3).

[15] According to the reconstructed historical data sets, China experienced substantial land use and land cover change during the twentieth century [Liu *et al.*, 2005a, 2005b; Liu and Tian, 2010]. The cropland area decreased by 11.6 million ha, while built-up areas increased by 9.3 million ha and forested area showed a net increase of 34.7 million ha over the period 1961–2005. The dominant land use and land cover change in this period was land transformation from grassland and shrub to cropland and from cropland to built-up land [Ge *et al.*, 2008; Liu *et al.*, 2005a, 2005b]. In addition to these temporal trends, substantial spatial variations in land use and land cover change took place across China during this time period [Liu *et al.*, 2005a, 2005b; Liu and Tian, 2010].

2.3. Model Implementation

[16] To determine the initial conditions of 1 January 1901, DLEM was fed with detrended climate data during 1901–1930. The levels of atmospheric CO₂ concentration, O₃ AOT40 index, nitrogen deposition, nitrogen fertilizer application, irrigation and land use pattern in the year of 1900 were used for the equilibrium run. A spin-up of 3000 years was applied after reaching an equilibrium state. That is, the absolute value of annual NCE (net balance of CO₂ and CH₄ fluxes) is less than 0.1 g C m⁻², the change in soil water pool is less than 0.1 mm, and the difference in soil mineral nitrogen content and N uptake is less than 0.1 g N m⁻² among consecutive years. Finally, the model was run in transient mode, where the simulated GHG budget was determined by the time series of multiple environmental changes from 1901 to 2005. We started the simulation in the year 1901 in order to capture the legacy effects of changes in land conversion, climate, nitrogen, O₃, and atmospheric CO₂, on greenhouse gas fluxes. This study focused on highlighting the simulation results during 1961–2005, when great changes in both natural and anthropogenic perspectives were taking place across China.

2.4. GWP Calculation

[17] The GWP index was defined to measure the time-integrated global mean radiative forcing of a pulse emission of 1 kg of a certain compound relative to that of 1 kg CO₂ [Forster *et al.*, 2007]. According to the fourth Intergovernmental Panel on Climate Change (IPCC) report, the average GWPs for CO₂, CH₄ and N₂O are 1, 25 and 298 at a 100 year time horizon, respectively. In this study, we applied the following equation to calculate annual GWP:

$$GWP = F_{CO_2-C} \frac{44}{12} + F_{CH_4-C} \frac{16}{12} \times RF_{CH_4} + F_{N_2O-N} \frac{44}{28} \times RF_{N_2O}$$

where F_{CO_2-C} , F_{CH_4-C} and F_{N_2O-N} are annual fluxes of CO₂, CH₄ and N₂O between terrestrial ecosystems and the atmosphere based on mass of C and N, respectively. The fractions 44/12, 16/12 and 44/28 were used to convert the mass of CO₂-C, CH₄-C and N₂O-N into CO₂, CH₄ and N₂O. RF_{CH_4} and RF_{N_2O} are constants indicating radiative forcing of CH₄ and N₂O in terms of a CO₂ equivalent unit, and were assigned

values of 25 and 298, respectively, at 100 year time horizon [Forster *et al.*, 2007].

2.5. Uncertainty Analysis

[18] Uncertainties in the simulated regional terrestrial fluxes of CO₂, CH₄, and N₂O were evaluated through a global sensitivity and uncertainty analysis as described by Xu [2010]. First, we assumed that the distribution of each parameter follows normal distribution based on our previous calibration experience [Tian *et al.*, 2010a]. Second, we conducted sensitivity analysis to identify the major parameters that affect terrestrial CO₂, CH₄, and N₂O fluxes, and determine the distribution of each parameter in controlling these fluxes; the sensitivity analysis was conducted by evaluating the changes in simulated gas fluxes in response to a 20% increase and decrease of each parameter. Third, combined with the priori knowledge of parameters, we used improved Latin Hypercube Sampling (LHS) approach to randomly select an ensemble of 300 sets of 10 parameters responsible for CO₂, CH₄, and N₂O fluxes simulated by the Dynamic Land Ecosystem Model (DLEM). We set up the simulations by using the sampled 300 pairs of parameters. Finally, the outlier simulations which generated extreme fluxes for CO₂, CH₄, or N₂O will be excluded before analyzing the parameter-derived uncertainties in GHG fluxes. The 95% confidence intervals for GHG fluxes were calculated and reported.

2.6. Statistical Calculation

[19] The regression analysis was used in this study to calculate the long-term changing rates of input data and GHGs fluxes. All the statistical analyses were conducted by using the software R-program and SPSS 17.0 for Windows XP.

3. Results

3.1. National Budgets of GHGs and GWP

[20] Our model simulations indicate that China's terrestrial ecosystems acted as a net CO₂ sink with a sequestration rate of 179.3 ± 102.2 Tg C yr⁻¹, and as a net source of CH₄ and N₂O at rates of 8.3 ± 1.5 Tg C yr⁻¹ and 0.6 ± 0.3 Tg N yr⁻¹, respectively, during 1961–2005. Over the study period, CO₂ flux in China's terrestrial ecosystems showed substantial interannual variability, ranging from a CO₂ source at a rate of 48.0 Tg C yr⁻¹ in 1997 to a CO₂ sink at a rate of 415.6 Tg C yr⁻¹ in 2002; the CH₄ and N₂O fluxes also showed considerable fluctuations, the CH₄ emission could be as high as 10.4 Tg C yr⁻¹ in 1973 or as low as 4.1 Tg C yr⁻¹ in 1978, and the N₂O emission was as high as 1.3 Tg N yr⁻¹ in 2005 and as low as 0.3 Tg N yr⁻¹ in 1966. Uncertainty analysis showed that the 95% confidence range for the fluxes of CO₂, CH₄, and N₂O are (62.0 Tg C yr⁻¹, 264.9 Tg C yr⁻¹), (3.3 Tg C yr⁻¹, 12.4 Tg C yr⁻¹), and (0.2 Tg N yr⁻¹, 1.1 Tg N yr⁻¹), respectively (Figure 4).

[21] In terms of global warming potential, national level CO₂ uptake served to mitigate GWP at a rate of 657.5 ± 374.9 Tg CO₂eq yr⁻¹, while national CH₄ and N₂O emissions proved to be enhancers of GWP at rates of 275.1 ± 48.3 Tg CO₂eq yr⁻¹ and 285.5 ± 131.0 Tg CO₂eq yr⁻¹ at a 100 year time horizon. Therefore, simultaneously taking China's three biogenic GHGs into account, we found that

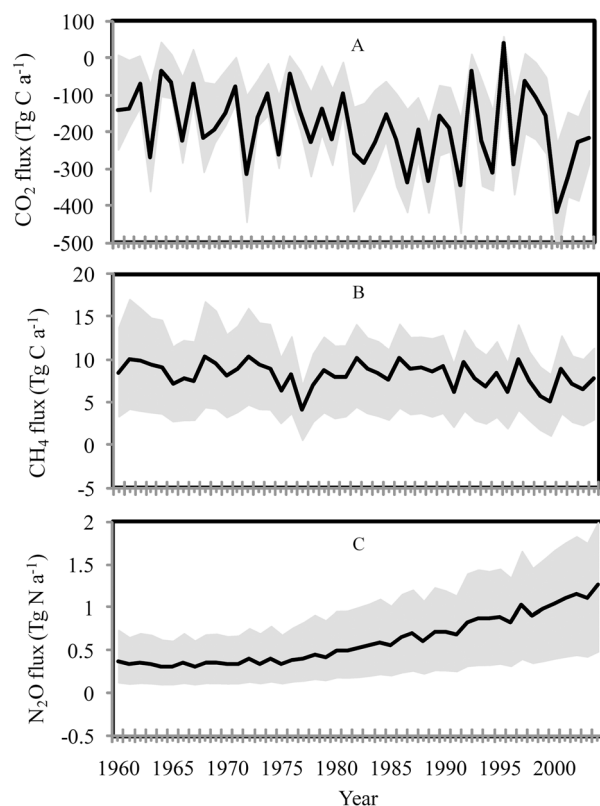


Figure 4. Temporal variations in GWP derived from fluxes of (a) CO₂, (b) CH₄, and (c) N₂O in China's terrestrial ecosystems. (Shaded area shows 95% confidence boundaries of GHGs fluxes.)

GHG-driven climate change was prone to be cooling with a GWP average of 96.9 ± 338.8 Tg CO₂eq yr⁻¹, ranging from a GWP enhancer at a rate of 766.8 Tg CO₂eq yr⁻¹ in 1997 to a GWP mitigator at a rate of 705.2 Tg CO₂eq yr⁻¹ in 2002, during the past 45 years. Our simulated results also indicate that CH₄ and N₂O emissions offset approximately 84.8% of

terrestrial CO₂ sink in China's terrestrial ecosystems for the study period.

3.2. Temporal Patterns of the GHG Fluxes and GWP

[22] Over the past 45 years, there has been a substantial interannual variation in the net exchanges of GHGs between land surface and the atmosphere across China's terrestrial ecosystems (Figure 4). Over the study period, no significant changing rate was observed for CO₂ flux, while a marginal significantly decreasing rate of 38.0 ± 15.8 Gg C yr⁻¹ ($1\text{Gg} = 10^9$ g) was observed for CH₄ emission ($0.05 < P < 0.10$), and a significantly increasing rate of 21.1 ± 1.1 Gg N yr⁻¹ was observed for N₂O emission ($P < 0.001$).

[23] We summarized the temporal patterns of the global warming potential induced by the fluxes of GHGs in Figure 5. From 1961 through 1990, a 5 year average GWP showed a slightly decreasing trend due to increased terrestrial CO₂ sequestration. However, since the 1990s, GWP resulting from biogenic GHGs began to shift from negative to positive, indicating that global radiative forcing owing to China's terrestrial GHG budgets had accumulated in this decade. The decline of CO₂ uptake in the 1990s might have been due to decreases in woodland area [Liu and Tian, 2010], rapid urban sprawl [Liu et al., 2005a, 2005b], and climate change [Chen et al., 2006]. Owing to an increased CO₂ uptake rate, GWP once again fell to negative values during 2001–2005. The lowest 5 year average net GWP occurred during 1986–1990, and the highest appeared in the period 1996–2000.

[24] Due to the broad uncertainty range of calculated GWP (Figure 5), we used 90% and 50% confidence boundaries to show the changes of GWP along the study period. The changes in GWP estimated by the DLEM is beyond the 50% confidence boundaries; for example, the upper boundary of 50% confidence boundary decreased to lower than the GWP estimated by DLEM in 1986–1990, and then increased; this indicates that it is more than 50% possibility that the reported changing pattern in GWP would occur (Figure 5).

3.3. Spatial Variations of the GHGs and GWP

[25] The biogenic fluxes of three GHGs varied substantially across China's terrestrial ecosystems. As far as CO₂ and

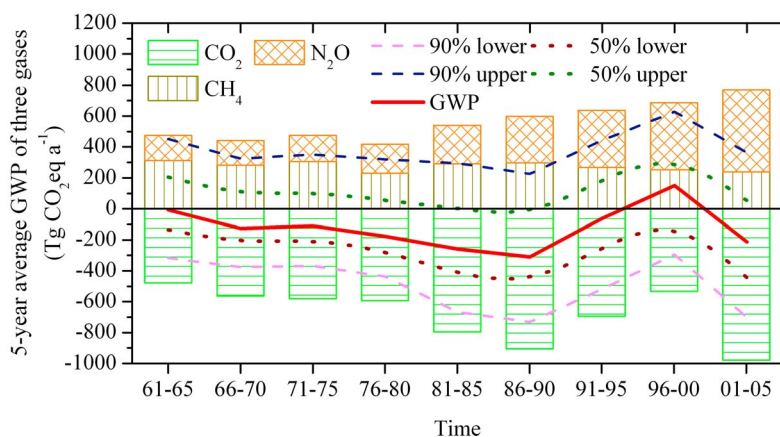
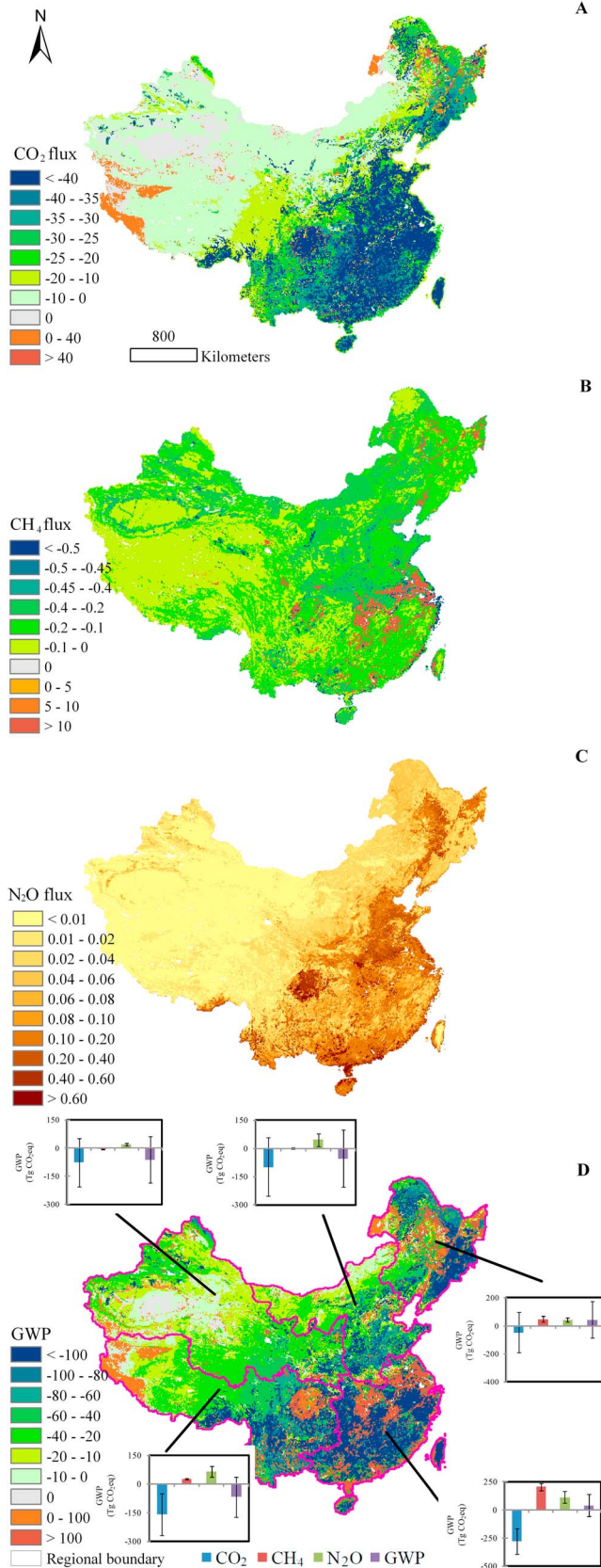


Figure 5. Temporal variations in fluxes of CO₂, CH₄, and N₂O and their uncertainty ranges in China's terrestrial ecosystems (90% upper and lower represent the upper and lower boundary of 90% confidence interval, respectively; 50% upper and lower represent the upper and lower boundary of 50% confidence interval, respectively; negative values indicate uptake, and positive values indicate release).



N₂O fluxes are concerned, apparent gradient was observed from southeastern China to northern and northwestern China (Figures 6a and 6c), while CH₄ emission peaked in the midsoutheast and northeast and the lowest emission or uptake was located in the central part of the mainland and northern region (Figure 6b). Over the study period, northwestern China accumulatively sequestered 0.94 Pg CO₂-C while emitting 6.24 Tg CH₄-C and 1.83 Tg N₂O-N; northern China accumulatively sequestered 1.21 Pg CO₂-C and oxidized 0.45 Tg CH₄-C while emitting 4.33 Tg N₂O-N; northeastern China accumulatively sequestered 0.59 Pg CO₂-C while emitting 65.89 Tg CH₄-C and 4.12 Tg N₂O-N; southwestern China accumulatively sequestered 1.95 Pg CO₂-C while emitting 36.22 Tg CH₄-C and 6.20 Tg N₂O-N; southeastern China accumulatively sequestered 3.39 Pg CO₂-C, while emitting 275.94 Tg CH₄-C and 10.95 Tg N₂O-N.

[26] Among the five regions, southeastern China acted as the strongest CO₂ sink as well as the largest source of CH₄ and N₂O to the atmosphere. The overall global warming potential in this region averaged to 42.46 ± 99.21 Tg CO₂eq yr⁻¹ or nearly neutral over the past 45 years. It should be noted that large interannual variation existed in the contribution of biogenic GHGs from this area to the cumulative radiative forcing during 1991–2005. In terms of GWP, northeastern China, in addition to the southeastern China, is another neutral player with a rate of 43.77 ± 128.58 Tg CO₂eq yr⁻¹ over the past 45 years.

[27] In contrast, the other three regions exhibited a negative global warming potential with large interannual variability, which were averaged to 67.23 ± 103.97 Tg CO₂eq yr⁻¹, 61.98 ± 124.26 Tg CO₂eq yr⁻¹, and 53.96 ± 150.61 Tg CO₂eq yr⁻¹ for southwestern, northwestern, and northern China, respectively. This indicates that CO₂ uptake played a predominant role in the GHG budgets in such areas, and therefore, the terrestrial ecosystems in these three regions played an important role in alleviating global warming resulting from three major biogenic GHG fluxes. During 1961–2005, regional average GHG fluxes showed that all five regions were sinks of atmospheric CO₂ and sources of N₂O, while CH₄ uptake occurred in northwestern and northern China, and the other three regions acted as CH₄ emitters.

3.4. Biome-Level GHGs and GWP

[28] The accumulative radiative forcing due to GHG budgets in China varied among biome types. Forests acted as the strongest CO₂ sink by sequestering 3.09 Pg CO₂-C over the past 45 years, while grassland and woodland sequestered CO₂ with the orders of 1.53 and 1.01 Pg CO₂-C, respectively. Grassland was the largest CH₄ sink, accumulatively withdrawing 20.94 Tg CH₄-C during the period

Figure 6. The 45 year average of ecosystem-atmosphere exchange of (a) CO₂ (units: g C m⁻² yr⁻¹), (b) CH₄ (units: g C m⁻² yr⁻¹), and (c) N₂O (units: g N m⁻² yr⁻¹), and (d) the resulted global warming potential (GWP) over China (units: g CO₂eq m⁻² yr⁻¹). (Note: the different scale of the y axis of insets in Figure 6d; negative values indicate uptake, and positive values indicate release; the error bars in insets represent standard deviation of GWP over the 45 years.)

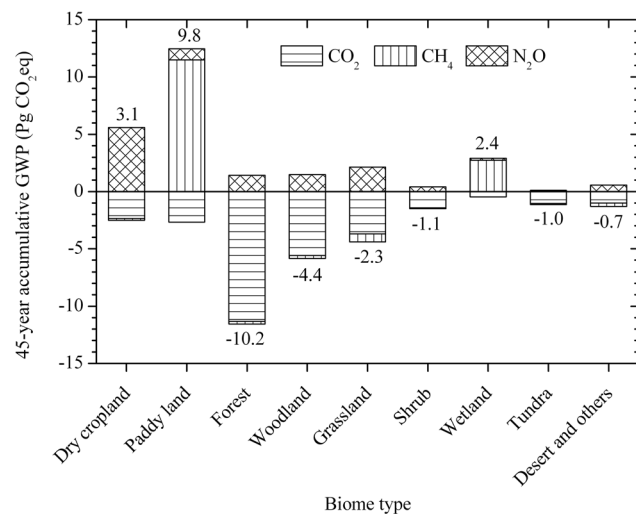


Figure 7. Contributions of various biomes to GWP over China's terrestrial ecosystem during 1961–2005. (Numbers above or below the bars are the net GWPs of three GHGs; negative values indicate cooling effect, and positive values indicate warming effect on climate system.)

1961–2005, followed by desert and others (7.75 Tg CH₄-C), forests (7.59 Tg CH₄-C), and woodland (7.58 Tg CH₄-C). It should be noted that the majority of desert in western China has a very low capacity for CH₄ oxidation due to extreme drought and lower biological activity. As for N₂O emission, the combined contribution from forest, woodland and grassland totals 10.02 Tg N₂O-N, yet is less than the N₂O released from dry cropland alone (11.94 Tg N₂O-N). Besides these three biomes, shrub land, tundra, and desert and other showed weak capacity for mitigating warming potential through sequestering CO₂ and oxidizing CH₄.

[29] When translated into GWP, forest, woodland and grassland turned out to be mitigators of climate warming (Figure 7) because the CO₂ sequestration and CH₄ oxidation-induced negative GWP in these biomes exceeded N₂O emission-induced positive GWP. China's forest played a critical role in relieving global warming, with a 45 year accumulative GWP of 10.2 Pg CO₂eq. Woodland and grassland were the second and third largest mitigators of GWP, with GWPs of 4.4 Pg CO₂eq and 2.3 Pg CO₂eq, respectively, accumulated over the study period.

[30] By contrast, accumulated GWP in both natural wetland and agricultural land (including rice paddy land and dry cropland) was positive over the past 45 years because the impacts of CH₄ and N₂O emissions on global warming were overwhelming in these ecosystems. Paddy land was the greatest contributor to national GWP due to the biogenic GHG budgets, with a 45 year cumulative value of 9.78 Pg CO₂eq, followed by dry cropland and natural wetland, in the order of 3.08 Pg CO₂eq and 2.4 Pg CO₂eq, respectively. Although both paddy land and natural wetland acted as net sinks of CO₂, sequestering 0.73 and 0.13 Pg C, respectively, during the past decades, they turned out to be contributors to GWP owing to their large emission of CH₄. From 1961 to 2005, paddy land accumulatively released 344.71 Tg CH₄-C, followed by natural wetland with a CH₄ emission

of 82.29 Tg C. In these two biomes, as *Friborg et al.* [2003] argued, CH₄ emission had a stronger effect than CO₂ sequestration on climate warming. Dry cropland ranked first in emitting N₂O to the atmosphere with total emissions of 11.94 Tg N₂O-N; its effect outweighed the cooling effects of CO₂ sequestration and CH₄ oxidation.

[31] The different contributions of various biomes to the biogenic GHG budget may explain the spatial variations of net GWP throughout China. Southeast China's role as a distinguished accelerator of global warming potential in certain years can be mainly attributed to its large proportion of rice paddies which released a great amount of CH₄. Likewise, a large area of natural wetland, which characterizes northeast China, substantially contributed to CH₄ emission. In addition, the spatial heterogeneity of net GWP may also be caused by the impacts of spatial variation in environmental factors, including climatic condition, ozone pollution, nitrogen input, and land use/cover change throughout the historical period, on biogenic GHG budgets.

4. Discussion

4.1. Comparison With Previous Studies

[32] To evaluate the reliability and robustness of our simulated results, we compared our modeled results to estimates from other studies at both site and regional levels. At the national level, China's terrestrial CO₂ uptake simulated by DLEM (198.2 ± 113.6 Tg C yr⁻¹) is close to estimates of 186–261 Tg C yr⁻¹ for 1980–2002 [*Piao et al.*, 2009] and inversion results based on CarbonTracker (261 ± 88 Tg C yr⁻¹) for the time period 2000–2005 (Table 1); the simulated N₂O release from China's terrestrial ecosystems is 0.71 ± 0.17 Tg N yr⁻¹ during 1980–2000, which is slightly lower than an empirical estimate of 0.98 ± 0.03 Tg N yr⁻¹ by *Xu et al.* [2008].

[33] Biome-level comparisons suggest that the DLEM-derived estimates of net exchanges of CO₂, CH₄, and N₂O between terrestrial ecosystems and the atmosphere are consistent with other estimates based on different methods (Table 1). For example, we estimated the sink strength of atmospheric CO₂ to be 39.9 ± 32.3 Tg C yr⁻¹ for cropland, which is slightly higher yet comparable to 39 ± 11 Tg C yr⁻¹, as reported by *Huang and Sun* [2006]; DLEM-simulated CO₂ sinks are 18.8 ± 53.1 Tg C yr⁻¹, and 3.0 ± 1.7 Tg C yr⁻¹ for grassland and natural wetlands, respectively; both are consistent with other studies (Table 1) [*Duan et al.*, 2008; *Piao et al.*, 2009]. DLEM-simulated CH₄ emission from natural wetland is 1.42 ± 0.50 Tg C yr⁻¹ during 1995–2004, which is comparable to a measurement-based estimate of 1.32 Tg C yr⁻¹ [*Ding and Cai*, 2007]. Model simulations found that rice paddy was a net CH₄ source at a rate of 7.23 ± 1.04 Tg C yr⁻¹ during 1990–2005; this value falls at the high end of the range 4.52–7.25 Tg C yr⁻¹ (Table 1) [*Huang et al.*, 1998; *Wang et al.*, 2009; *Yan et al.*, 2009], but falls far lower than the estimate of 11.48 Tg C yr⁻¹ in 1991 in the work of *Yao et al.* [1996]. The differences between our results and previous studies could be partially explained by the different rice paddy areas accounted for; for example, *Huang et al.* [2006] used an area of 0.30 million km² in their estimations of CH₄ emission from China's rice paddy land in the year 2000; in contrast, we used 0.34 million km² in our study which was estimated from satellite data [*Liu*

Table 1. GHGs Fluxes From Chinese Terrestrial Ecosystems Using Different Approaches^a

Gases	Biome	Method	Period	Area (million km ²)	Fluxes		Reference	
					(T g C yr ⁻¹ for CO ₂ and CH ₄ ;	T g N yr ⁻¹ for N ₂ O)		
CO ₂	all biomes	inventory-based, process-based model, and inversion results	1980–2002		-186~-261		<i>Piao et al.</i> [2009]	
	all biomes	process-based model	1980–2002		-198.2 ± 113.6		this study	
	all biomes	inversion results	2000–2005		-261 ± 88 ^b		carbon tracker	
	all biomes	process-based model	2000–2005		-238.1 ± 115.4		this study	
	cropland	inventory-based method	1980–2002	1.2~1.6	-39 ± 11		<i>Piao et al.</i> [2009]	
	cropland	process-based model	1980–2002	1.33~1.44	-39.9 ± 32.3		this study	
	grassland	inventory-based method	1980–2002	3.31	-7 ± 2		<i>Piao et al.</i> [2009]	
	grassland	process-based model	1980–2002	3.51~3.53	-18.8 ± 53.1		this study	
	natural wetland	field observations extrapolation	1990s	0.094	-5.2 ^c		<i>Duan et al.</i> [2008]	
	natural wetland	process-based model	1990s	0.091~0.097	-3.0 ± 1.7		this study	
CH ₄	all biomes	process-based model	1961–2005		8.3 ± 1.5		this study	
	natural wetland	process-based model	1995–2004	0.091~0.095	1.42 ± 0.50		this study	
	natural wetland	site extrapolation	1995–2004	0.094	1.32		<i>Ding and Cai</i> [2007]	
	rice paddy	empirical approach	2000		5.56		<i>Yan et al.</i> [2009]	
	rice paddy	semiempirical model	1995 for 1998 study and 2000 for 2006 and 2009 studies	0.302	4.52~7.25		<i>Huang et al.</i> [1998, 2006] and <i>Wang et al.</i> [2009]	
	rice paddy	regional classification	1991	0.32	11.48		<i>Yao et al.</i> [1996]	
	rice paddy	process-based model	1990–2005	0.32~0.37	7.23 ± 1.04		this study	
	N ₂ O	all biomes	empirical method	1980–2000		0.98 ± 0.03		<i>Xu et al.</i> [2008]
		all biomes	process-based model	1980–2000		0.71 ± 0.17		this study
		cropland	empirical model	1995		0.476		<i>Yan et al.</i> [2003a]
cropland		site observations extrapolation	1995	0.9497	0.398		<i>Xing</i> [1998]	
cropland		process-based model	1995	1.38	0.56		this study	
cropland		empirical approach	1990s		0.059~0.647		<i>Zheng et al.</i> [2004]	
cropland		process-based model	1990s	1.37~1.40	0.53 ± 0.08		this study	
temperate grassland		site observations extrapolation	1990s ^c	2.87~3.53	0.0404~0.112		<i>Chen et al.</i> [2000] and <i>Huang et al.</i> [2003]	
temperate grassland		process-based model	1990s	1.73~1.74	0.10 ± 0.01		this study	

^aNegative values indicate uptake, while positive values indicate emission.^bDerived from carbon tracker website (<http://www.esrl.noaa.gov/gmd/ccgg/carbontracker/>).^cBased on the field observations data used in the estimations.

Table 2. Comparison With Global Fluxes of CO₂, CH₄, N₂O, and GWP for the 1980s and the 1990s^a

	CO ₂ (Pg C yr ⁻¹)	CH ₄ (Tg C yr ⁻¹)	N ₂ O (Tg N yr ⁻¹)	GWP (Tg CO ₂ eq yr ⁻¹)
China	-0.19	8.44	0.70	-105.8
Global estimates	-1.95 (-2.6~-1.7) ^b	106.5 (52.5~153.75) ^c	9.4 (5~13.8) ^d	801.89 (-5808.57~5354.01)

^aFor gas fluxes, negative values indicate uptake, and positive values indicate release; global estimates are from *Denman et al.* [2007].

^bLand ecosystems only [*Denman et al.*, 2007].

^cEmission from wetland and soil consumption of atmospheric CH₄.

^dSource from both agricultural and natural soils across the globe.

et al., 2005a, 2005b]. At the same time, management practices might be another reason for the estimation gaps [*Li et al.*, 2005]. For example, *Huang et al.* [1998] estimated the CH₄ source in China's rice paddy land to be 7.25 Tg C yr⁻¹ in their early study, assuming a continuous flooding water regime, but later changed their estimate to 4.52 Tg C yr⁻¹ when field drainage was considered [*Huang et al.*, 2006]. Our results show that cropland acted as a source of N₂O at a rate of 0.56 Tg N yr⁻¹ in the year 1995, which is consistent with reports by *Yan et al.* [2003a], *Xing* [1998], and *Zheng et al.* [2004]; DLEM-estimated N₂O source for temperate grassland is 0.10 ± 0.01 Tg N yr⁻¹, which falls in the reported range of 0.04~0.112 Tg N yr⁻¹ during the 1990s. Therefore, it is confirmed that DLEM is capable of reasonably estimating the magnitude of terrestrial uptake and release of CO₂, CH₄ and N₂O throughout China.

4.2. Control of Interannual Variations in National GWP

[34] To further evaluate the influence of GHGs on interannual variation in national GWP, we conducted a regression analysis. A significantly positive correlation was found between annual GWP and net exchange of CO₂ between terrestrial ecosystems and the atmosphere ($R^2 = 0.88$; $N = 45$; $P < 0.001$); even so, no significant correlation emerged between interannual GWP and terrestrial flux of either CH₄ or N₂O. This suggests that the interannual variability in net GWP derived from China's biogenic GHGs balance was dominated by net exchange of CO₂ between terrestrial ecosystems and the atmosphere, since CH₄ fluxes remained relatively stable and N₂O emission kept increasing, but was not potent enough to shape the net GWP over the study period. However, the contributions of CH₄ and N₂O, which determined the magnitude of GWP, were overwhelming during the warming decade of 1990–2000, during which the terrestrial CO₂ sequestration rate shrank.

4.3. Global Implications

[35] This study provides a comprehensive evaluation of the fluxes of three GHGs throughout China's terrestrial ecosystems. Putting our estimates in the context of the global fluxes of these GHGs, China's terrestrial ecosystems acted as a small mitigator for climate warming (Table 2). The summarized estimates on the fluxes of CO₂, CH₄, and N₂O in the IPCC report indicated that the global land ecosystems sequestered CO₂ at a rate of 1.95 Pg C yr⁻¹, while emitted CH₄ and N₂O at rates of 106.5 Tg C yr⁻¹ and 9.4 Tg N yr⁻¹, respectively, over the 1980s and 1990s (Table 2). Thus, as a whole, the global land ecosystems functioned as an enhancer for climate warming at a rate of 801.9 Tg CO₂eq yr⁻¹, substantially varying from a sink at a rate of 5808.6 Tg

CO₂eq yr⁻¹ to a source at a rate of 5354.0 Tg CO₂eq yr⁻¹. In comparison, China's terrestrial ecosystems acted as a mitigator of climate warming at a rate of 105.8 Tg CO₂eq yr⁻¹ during the same time period.

4.4. Uncertainties and Improvements Needed

[36] This study, to the best of our knowledge, provides the first regional and national estimates of long-term net GWP of CO₂, CH₄, and N₂O over China's terrestrial ecosystems. Several uncertainties exist and further research is needed to improve our estimates. First, the driving forces of the model might introduce some uncertainties; for example, the area of natural wetlands (or in this case, mire) used in this study is 0.091–0.107 million km², which is close to inventoried results [*Zhao*, 1999], but is slightly lower than other estimates [*An et al.*, 2007; *Niu et al.*, 2009]. Given the considerably large difference in CH₄ flux from different wetlands [*Song et al.*, 2009], and high uncertainty in wetland area estimates [*An et al.*, 2007; *Niu et al.*, 2009], there is a great need for improving data accuracy in the future. Second, intensive management on plantation forest, such as application of fertilizer, thinning, etc., was not included in the current study, and needs to be emphasized. Third, the model may oversimplify the biogeochemical and microbial processes responsible for GHGs production and consumption; for example, an atmospheric N₂O sink in soil has been reported in several field studies, but the mechanisms for N₂O sequestration in soil are still unclear [*Chapuis-Lardy et al.*, 2007]; the inclusion of this mechanism might improve model accuracy in the estimation of national N₂O flux. Fourth, the agricultural system is a highly human-dominated ecosystem which needs time series of spatially explicit data on agricultural practices across the nation for accurately estimating GHG budgets. Although our study includes irrigation, water management, harvest, fertilization and, rotation, we need to address some uncertainties associated with areas of dry cropland and rice paddies, water regime during water management, manure application, etc. [*Huang et al.*, 2006; *Zou et al.*, 2005].

5. Conclusion

[37] Our simulation results indicated that China's terrestrial ecosystems were a small mitigator of global warming potential in terms of three GHG budgets during 1961–2005, even though large amounts of CH₄ and N₂O were released during this period. Approximately 84.8% of the cooling effects induced by terrestrial CO₂ sink were offset by terrestrial CH₄ and N₂O emissions in China. We also found that large interannual variations in biogenic GHG contributions to climate change existed on national scale. Southeast and northeast China were the neutral areas contributing little to

warming potential over the past 45 years, even though GWP values in these two regions shifted significantly from negative to positive since 1990. By contrast, the accumulated negative radiative forcing due to prevailing terrestrial CO₂ uptake in northwest, north, and southwest China considerably reduced the impact of GHGs on climate warming. Paddy land was the greatest contributor to national GWP, followed by natural wetland and dry cropland. China's forest area played a critical role in alleviating warming potential, with grassland and woodland as the second and third mitigators. Comparing to global terrestrial ecosystems acting as an enhancer of climate warming, China's land ecosystems functioned as a mitigator of climate warming for the past 45 years.

[38] Studies on concurrent net exchanges of greenhouse gases between land surface and the atmosphere, rather than a certain GHG species, would provide more profound insights for scientific communities and policy makers striving to curb climatic warming. We are calling for more site-level experiments highlighting fluxes of multiple GHGs and their interactions to validate process-based model results, and extrapolate their underlying mechanisms to wider ranges. In addition to accurately quantifying GHG budgets, future work is greatly needed to investigate the contributions of multiple environmental changes which control global warming potential by affecting GHG budgets.

[39] **Acknowledgments.** This study has been supported by NASA LCLUC Program (NNX08AL73G_S01), NASA IDS Program (NNG04GM39C), and China's Ministry of Science and Technology (MOST) 973 Program (2002CB412500). We thank Yao Huang in Institute of Atmospheric Physics, Chinese Academy of Sciences (CAS), Xiaoyuan Yan in Institute of Soil Science, CAS, and all members of the Ecosystem Dynamics and Global Ecology (EDGE) Lab for their helpful comments and discussions. We also appreciate Dennis Baldocchi and two anonymous reviewers for their constructive comments which greatly improved this manuscript.

References

- An, S., et al. (2007), China's natural wetlands: Past problems, current status, and future challenges, *Ambio*, 36(4), 335–342.
- Baldocchi, D. (2008), Breathing of the terrestrial biosphere: Lessons learned from a global network of carbon dioxide flux measurement systems, *Aust. J. Bot.*, 56(1), 1–26.
- Blais, A. M., S. Lorrain, and A. Tremblay (2005), Greenhouse gas fluxes (CO₂, CH₄ and N₂O) in forests and wetlands of boreal, temperate and tropical regions, in *Greenhouse Gas Emissions—Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments*, edited by A. Tremblay et al., Springer, New York.
- Chapuis-Lardy, L., N. Wrage, A. Metay, J. L. Chotte, and M. Bernoux (2007), Soils, a sink for N₂O? A review, *Global Change Biol.*, 13(1), 1–17.
- Chen, G., H. Tian, M. Liu, W. Ren, C. Zhang, and S. Pan (2006), Climate impacts on China's terrestrial carbon cycle: An assessment with the dynamic land ecosystem model, in *Environmental Modelling and Simulation*, edited by H. Q. Tian, pp. 56–70, ACTA Press, Anaheim, Calif.
- Chen, G. X., B. Huang, H. Xu, Y. Zhang, G. H. Huang, K. W. Yu, A. X. Hou, R. Du, S. J. Han, and O. VanCleemput (2000), Nitrous oxide emissions from terrestrial ecosystems in China, *Chemosphere*, 2, 373–378.
- Conrad, R. (1996), Soil microorganisms as controllers of atmospheric trace gases (H₂, CO, CH₄, OCS, N₂O, and NO), *Microbiol. Rev.*, 60(4), 609–640.
- Davidson, E. A., M. Keller, H. Erickson, L. V. Verchot, and E. Veldkamp (2000), Testing a conceptual model of soil emissions of nitrous and nitric oxides, *BioScience*, 50(8), 667–680.
- Denman, K. L., et al. (2007), Couplings between changes in the climate system and biogeochemistry, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, New York.
- Ding, W. X., and Z. C. Cai (2007), Methane emission from natural wetlands in China: Summary of years 1995–2004 studies, *Pedosphere*, 17(4), 475–486.
- Duan, X., X. Wang, F. Lu, and Z. Ouyang (2008), Primary evaluation of carbon sequestration potential of wetlands in China, *Acta Bot. Sin.*, 28(2), 463–469.
- Fang, J., A. Chen, C. Peng, S. Zhao, and L. Ci (2001), Changes in forest biomass carbon storage in China between 1949 and 1998, *Science*, 292(5525), 2320.
- Fang, J., Z. Guo, S. Piao, and A. Chen (2007), Terrestrial vegetation carbon sinks in China, 1981–2000, *Sci. China, Ser. D*, 50(9), 1341–1350.
- Forster, P., et al. (2007), Changes in atmospheric constituents and in radiative forcing, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, New York.
- Friborg, T., H. Soegaard, T. Christensen, C. Lloyd, and N. Panikov (2003), Siberian wetlands: Where a sink is a source, *Geophys. Res. Lett.*, 30(21), 2129, doi:10.1029/2003GL017797.
- Ge, Q. S., J. H. Dai, F. N. He, Y. Pan, and M. M. Wang (2008), Land use changes and their relations with carbon cycles over the past 300 a in China, *Sci. China, Ser. D*, 51(6), 871–884.
- Gregg, J. S., R. J. Andres, and G. Marland (2008), China: Emissions pattern of the world leader in CO₂ emissions from fossil fuel consumption and cement production, *Geophys. Res. Lett.*, 35, L08806, doi:10.1029/2007GL032887.
- Huang, B., G. Chen, G. Huang, and T. Hauro (2003), Nitrous oxide emission from temperate meadow grassland and emission estimation for temperate grassland of China, *Nutr. Cycl. Agroecosyst.*, 67, 31–36.
- Huang, G. H., X. Z. Li, Y. M. Hu, Y. Shi, and D. N. Xiao (2005), Methane (CH₄) emission from a natural wetland of northern China, *J. Environ. Sci. Health, Part A*, 40(6–7), 1227–1238.
- Huang, Y., and W. Sun (2006), Changes in topsoil organic carbon of croplands in mainland China over the last two decades, *Chin. Sci. Bull.*, 51(15), 1785–1803.
- Huang, Y., R. L. Sass, and F. M. Fisher (1998), Model estimates of methane emission from irrigated rice cultivation of China, *Global Change Biol.*, 4, 809–821.
- Huang, Y., W. Zhang, X. Zheng, S. Han, and Y. Yu (2006), Estimates of methane emissions from Chinese rice paddies by linking a model to GIS database, *Acta Ecol. Sin.*, 26(4), 980–988.
- Huang, Y., W. Sun, W. Zhang, Y. Yu, Y. Su, and C. Song (2009), Marshland conversion to cropland in northeast China from 1950 to 2000 reduced the greenhouse effect, *Global Change Biol.*, 16(2), 680–695, doi:10.1111/j.1365-2486.2009.01976.x.
- Law, B. E., et al. (2002), Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, *Agric. For. Meteorol.*, 113(1–4), 97–120.
- Li, C., S. Frolking, X. Xiao, B. Moore III, S. Boles, J. Qiu, Y. Huang, W. Salas, and R. Sass (2005), Modeling impacts of farming management alternatives on CO₂, CH₄, and N₂O emissions: A case study for water management of rice agriculture of China, *Global Biogeochem. Cycles*, 19, GB3010, doi:10.1029/2004GB002341.
- Lin, B., A. Sakoda, R. Shibasaki, N. Goto, and M. Suzuki (2000), Modeling a global biogeochemical nitrogen cycle in terrestrial ecosystems, *Ecol. Modell.*, 135, 89–110.
- Liu, J., H. Tian, M. Liu, D. Zhuang, J. M. Melillo, and Z. Zhang (2005a), China's changing landscape during the 1990s: Large-scale land transformations estimated with satellite data, *Geophys. Res. Lett.*, 32, L02405, doi:10.1029/2004GL021649.
- Liu, J., M. Liu, H. Tian, D. Zhuang, Z. Zhang, W. Zhang, X. Tang, and X. Deng (2005b), Spatial and temporal patterns of China's cropland during 1990–2000: An analysis based on Landsat TM data, *Remote Sens. Environ.*, 98(4), 442–456.
- Liu, M., and H. Tian (2010), China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives, *Global Biogeochem. Cycles*, 24, GB3003, doi:10.1029/2009GB003687.
- Liu, M., H. Tian, G. Chen, W. Ren, C. Zhang, and J. Liu (2008), Effects of land-use and land-cover change on evapotranspiration and water yield in China during 1900–2000, *J. Am. Water Resour. Assoc.*, 44(5), 1193–1207.
- Lu, C. (2009), Study of atmospheric nitrogen deposition and terrestrial ecosystem carbon cycle in China, dissertation thesis, Chin. Acad. of Sci., Beijing.
- Lu, C., and H. Tian (2007), Spatial and temporal patterns of nitrogen deposition in China: Synthesis of observational data, *J. Geophys. Res.*, 112, D22S05, doi:10.1029/2006JD007990.
- Mer, J. L., and P. Roger (2001), Production, oxidation, emission and consumption of methane by soils: A review, *Eur. J. Soil Biol.*, 37, 25–50.

- Niu, Z., et al. (2009), Geographical characteristics of China's wetlands derived from remotely sensed data, *Sci. China, Ser. D*, 52(6), 723–738.
- Pan, Y., T. Luo, R. Birdsey, J. Hom, and J. M. Melillo (2004), New estimates of carbon storage and sequestration in China's forests: Effects of age-class and method on inventory-based carbon estimation, *Clim. Change*, 67(2), 211–236.
- Piao, S., J. Fang, P. Ciais, P. Peylin, Y. Huang, S. Sitch, and T. Wang (2009), The carbon balance of terrestrial ecosystems in China, *Nature*, 458(7241), 1009–1014.
- Qiu, J., C. Li, L. Wang, H. Tang, H. Li, and E. V. Ransat (2009), Modeling impacts of carbon sequestration on net greenhouse gas emissions from agricultural soils in China, *Global Biogeochem. Cycles*, 23, GB1007, doi:10.1029/2008GB003180.
- Ren, W., H. Tian, M. Liu, C. Zhang, G. Chen, S. Pan, B. Felzer, and X. Xu (2007), Effects of tropospheric ozone pollution on net primary productivity and carbon storage in terrestrial ecosystems of China, *J. Geophys. Res.*, 112, D22S09, doi:10.1029/2007JD008521.
- Ren, W., H. Tian, X. Xu, M. Liu, C. Lu, G. Chen, J. M. Melillo, J. Reilly, and J. Liu (2011a), Spatial and temporal patterns of CO₂ and CH₄ fluxes in China's croplands in response to multifactor environmental changes, *Tellus, Ser. B*, 63(2), 222–240, doi:10.1111/j.1600-0889.2010.00522.x.
- Ren, W., H. Tian, B. Tao, A. Chappelka, G. Sun, C. Lu, M. Liu, G. Chen, and X. Xu (2011b), Impacts of tropospheric ozone and climate change on net primary productivity and net carbon exchange of China's forest ecosystems assessed with the dynamic land ecosystem model (DLEM), *Global Ecol. Biogeogr.*, doi:10.1111/j.1466-8283.2010.00606.x.
- Repo, M. E., S. Susiluoto, S. E. L. Link, S. Jokinen, V. Elsakov, C. Biasi, T. Virtanen, and P. J. Martikainen (2009), Large N₂O emissions from cryoturbated peat soil in tundra, *Nat. Geosci.*, 2, 4.
- Rodhe, H. (1990), A comparison of the contribution of various gases to the greenhouse effect, *Science*, 248(4960), 1217–1219.
- Saleska, S. R., et al. (2003), Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses, *Science*, 302(5650), 1554–1557.
- Schimel, D. S., et al. (2001), Recent patterns and mechanisms of carbon exchange by terrestrial ecosystems, *Nature*, 414(6860), 169–172.
- Schulze, E. D., et al. (2009), Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance, *Nat. Geosci.*, 2(12), 842–850.
- Shui, J., X. Chai, and T. Lu (1999), Effects of precipitation on nutrient inputs and erosion of forest land, *Soil Environ. Sci.*, 8, 258–261.
- Song, C., X. Xu, H. Tian, and Y. Wang (2009), Ecosystem-atmosphere exchange of CH₄ and N₂O and ecosystem respiration in wetlands in the Sanjiang Plain, northeastern China, *Global Change Biol.*, 15, 692–705.
- Tang, X., S. Liu, G. Zhou, D. Zhang, and C. Zhou (2006), Soil-atmospheric exchange of CO₂, CH₄, and N₂O in three subtropical forest ecosystems in southern China, *Global Change Biol.*, 12, 546–560.
- Tian, H., M. Liu, C. Zhang, W. Ren, G. Chen, X. Xu, and C. Lu (2005), *DLEM—The Dynamic Land Ecosystem Model User Manual*, Auburn Univ., Auburn, Ala.
- Tian, H., X. Xu, C. Zhang, W. Ren, G. Chen, M. Liu, D. Lu, and S. Pan (2008), *Forecasting and Assessing the Large-Scale and Long-Term Impacts of Global Environmental Change on Terrestrial Ecosystems in the United States and China*, Springer, New York.
- Tian, H., X. Xu, M. Liu, W. Ren, C. Zhang, G. Chen, and C. Lu (2010a), Spatial and temporal patterns of CH₄ and N₂O fluxes in terrestrial ecosystems of North America during 1979–2008: Application of a global biogeochemistry model, *Biogeosciences*, 7, 2673–2694.
- Tian, H., G. Chen, M. Liu, C. Zhang, G. Sun, C. Lu, X. Xu, W. Ren, S. Pan, and A. Chappelka (2010b), Model estimates of net primary productivity, evapotranspiration, and water use efficiency in the terrestrial ecosystems of the southern United States during 1895–2007, *For. Ecol. Manage.*, 259, 1311–1327.
- Tian, H., et al. (2011), China's terrestrial carbon balance: Contributions from multiple global change factors, *Global Biogeochem. Cycles*, 25, GB1007, doi:10.1029/2010GB003838.
- Wang, P., Y. Huang, and W. Zhang (2009), Estimates of methane emission from rice paddies in China over the period of 1955–2005 by linking the CH4MOD model to a GIS database, *Adv. Clim. Change Res.*, 5(5), 291–297.
- Wofsy, S. C., M. L. Goulden, J. W. Munger, S. M. Fan, P. S. Bakwin, B. C. Daube, S. L. Bassow, and F. A. Bazzaz (1993), Net exchange of CO₂ in a midlatitude forest, *Science*, 260(5112), 1314–1317.
- Xing, G. X. (1998), N₂O emission from cropland in China, *Nutr. Cycl. Agroecosyst.*, 52, 249–254.
- Xu, X. (2010), Modeling methane and nitrous oxide exchange between the atmosphere and terrestrial ecosystems over North America in the context of multifactor global change, dissertation, Auburn Univ., Auburn, Ala.
- Xu, X., H. Tian, and D. Hui (2008), Convergence in the relationship of CO₂ and N₂O exchanges between soil and atmosphere within terrestrial ecosystems, *Global Change Biol.*, 14(7), 1651–1660.
- Xu, X., H. Tian, C. Zhang, M. Liu, W. Ren, G. Chen, C. Lu, and L. Bruhwiler (2010), Attribution of spatial and temporal variations in terrestrial ecosystem methane flux over North America, *Biogeosciences*, 7, 3637–3655.
- Yan, X., H. Akimoto, and T. Ohara (2003a), Estimation of nitrous oxide, nitric oxide and ammonia emissions from croplands in East, Southeast and South Asia, *Global Change Biol.*, 9, 1080–1096.
- Yan, X., Z. Cai, T. Ohara, and H. Akimoto (2003b), Methane emission from rice fields in mainland China: Amount and seasonal and spatial distribution, *J. Geophys. Res.*, 108(D16), 4505, doi:10.1029/2002JD003182.
- Yan, X., H. Akiyama, K. Yagi, and H. Akimoto (2009), Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines, *Global Biogeochem. Cycles*, 23, GB2002, doi:10.1029/2008GB003299.
- Yao, H., Y. Zhuang, and Z. Chen (1996), Estimation of methane emission from rice paddies in mainland China, *Global Biogeochem. Cycles*, 10(4), 641–649.
- Zhang, C., H. Tian, A. Chappelka, W. Ren, H. Chen, S. Pan, M. Liu, D. Styers, G. Chen, and Y. Wang (2007), Impacts of climatic and atmospheric changes on carbon dynamics in the Great Smoky Mountains National Park, *Environ. Pollut.*, 149(3), 336–347.
- Zhao, K. (1999), *Swamp Records of China*, Sci. Press, Beijing.
- Zheng, X., S. Han, Y. Huang, Y. Wang, and M. Wang (2004), Re-quantifying the emission factors based on field measurements and estimating the direct N₂O emission from Chinese croplands, *Global Biogeochem. Cycles*, 18, GB2018, doi:10.1029/2003GB002167.
- Zou, J., Y. Huang, L. Zong, X. Zheng, and Y. Wang (2004), Carbon dioxide, methane, and nitrous oxide emissions from a rice-wheat rotation as affected by crop residue incorporation and temperature, *Adv. Atmos. Sci.*, 21(5), 691–698.
- Zou, J., Y. Huang, J. Jiang, X. Zheng, and R. L. Sass (2005), A 3-year field measurement of methane and nitrous oxide emissions from rice paddies in China: Effects of water regime, crop residue, and fertilizer application, *Global Biogeochem. Cycles*, 19, GB2021, doi:10.1029/2004GB002401.
- Zou, J., Y. Huang, Y. Qin, S. Liu, Q. Shen, G. Pan, Y. Lu, and Q. Liu (2009), Changes in fertilizer induced direct N₂O emissions from paddy fields during rice growing season in China between 1950s and 1990s, *Global Change Biol.*, 15(1), 229–242.
- Zou, J., Y. Lu, and Y. Huang (2010), Estimates of synthetic fertilizer N-induced direct nitrous oxide emission from Chinese croplands during 1980–2000, *Environ. Pollut.*, 158(2), 631–635.

G. Chen, M. Liu, C. Lu, W. Ren, H. Tian, and X. Xu, Ecosystem Dynamics and Global Ecology Laboratory, School of Forestry and Wildlife Sciences, Auburn University, 602 Duncan Dr., Auburn, AL 36849, USA. (tianhan@auburn.edu)

J. Liu, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China.

J. Melillo, The Ecosystem Center, Marine Biological Laboratory, 7 MBL St., Woods Hole, MA 02543, USA.