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Summary of Recent Climate Change Studies on the Carbon and Nitrogen Cycles in the Terrestrial Ecosystem and Ocean in China

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ABSTRACT

This article reviews recent advances over the past 4 years in the study of the carbon-nitrogen cycling and their relationship to climate change in China. The net carbon sink in the Chinese terrestrial ecosystem was 0.19–0.26 Pg C yr^{-1} for the 1980s and 1990s. Both natural wetlands and the rice-paddy regions emitted 1.76 Tg and 6.62 Tg of CH_4 per year for the periods 1995–2004 and 2005–2009, respectively. China emitted ~1.1 Tg N_2O-N yr^{-1} to the atmosphere in 2004. Land soil contained ~8.3 Pg N. The excess nitrogen stored in farmland of the Yangtze River basin reached 1.51 Tg N and 2.67 Tg N in 1980 and 1990, respectively. The outer Yangtze Estuary served as a moderate or significant sink of atmospheric CO_2 except in autumn. Phytoplankton could take up carbon at a rate of 6.4 $\times 10^{11}$ kg yr^{-1} in the China Sea. The global ocean absorbed anthropogenic CO_2 at the rates of 1.64 and 1.73 Pg C yr^{-1} for two simulations in the 1990s. Land net ecosystem production in China would increase until the mid-21st century then would decrease gradually under future climate change scenarios. This research should be strengthened in the future, including collection of more observation data, measurement of the soil organic carbon (SOC) loss and sequestration, evaluation of changes in SOC in deep soil layers, and the impacts of grassland management, carbon-nitrogen coupled effects, and development and improvement of various component models and of the coupled carbon cycle-climate model.

Key words: carbon cycle, nitrogen cycle, climate change, Chinese terrestrial ecosystem, China Sea

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1. Introduction

Climate and life on the Earth are linked through various interacting cycles and feedback mechanisms. In recent decades, it has been recognized that global climate has been changing, particularly since the industrial revolution; this change is associated with biogeochemical cycles of elements, including the carbon and nitrogen cycles.

Both carbon and nitrogen are main components of living organisms. Carbon exists in the Earth's ecosystem in the many different forms such as CO_2, carbonate, and numerous organic compounds that are continuously cycled. Because of the burning of fossil fuels and carbon emissions from land-use change, atmospheric CO_2 has increased by >30% above the preindustrial level. Understanding carbon-cycle processes in the various reservoirs and their changes, recognizing the feedback mechanisms of the interactions of carbon cycle with climate change, ecosystems, and human activities, and projecting future climate change and its impacts are current hot topics in many research fields.

Nitrogen in the atmosphere is in a form (N_2) unavailable to most organisms. Microbes turn this nitrogen into nitrates and other compounds through the process of nitrogen fixation, in which plants or algae assimilate nitrogen into their tissues. As the world's human population increases, large amounts of nitro-

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gen fertilizers produced by the industrial process have been used to increase food production. Both the nitrogen used in food production and the nitrogen generated during fossil-fuel combustion are emitted into the environment. The increase of these sources of anthropogenic nitrogen affects the environment. In addition, accumulation of nitrogen in the environment leads to the increased interaction of nitrogen with other biogeochemical element cycles. It is important to understand whether and how these interactions affect global climate change.

Carbon and nitrogen are naturally tightly coupled; they occur with specific elemental stoichiometries (e.g., the Redfield ratio). Human activity has perturbed the global nitrogen and carbon cycles. The increased nitrogen available to plants probably stimulates their productivity. Hence, it is important to understand the processes that control the C:N ratios of autotrophic organisms on land and in the ocean. The carbon sink in the Northern Hemisphere terrestrial biosphere is due to CO_2 fertilization and/or nitrogen fertilization. Like CO_2, atmospheric N_2O has significantly increased. The connection between air temperature and atmospheric CO_2 and N_2O levels further demonstrates that global carbon and nitrogen cycles are closely coupled to climate change. Apart from CO_2, methane is another species containing carbon that has also significantly increased in the atmosphere; it is also an important greenhouse gas.

Chinese scientists have been working in related research fields for many years, and they have achieved a great deal. This paper summarizes some of this research work by Chinese scientists since 2006.

2. Terrestrial carbon and nitrogen cycles

Carbon cycle and carbon budgets in the terrestrial ecosystem play an important role in its response to global climate change. Recent research has shown that over last several years, the increase in atmospheric CO_2 accounted for ~45% of the global emission, and the rest has been absorbed by the land (30%) and oceans (25%). The terrestrial ecosystem consists of many different varieties of complicated systems. It is difficult to determine which systems are storing carbon and how much. Research indicates that over the last 20 years, the northern middle- and higher-latitude terrestrial ecosystem comprises a large carbon sink. It is important to determine whether the Chinese terrestrial ecosystem is a carbon sink and if so, how large the sink is.

2.1 *Carbon budget*

2.1.1 *Forest*

Forests covered 18.2% of China based on the 6th National Forest Inventory of an area of 1.749×10^6 km^2 completed during 1999–2003 (State Environmental Protection Administration, 2007). Using the National Forest Inventory data, Fang et al. (2007) determined that forest biomass carbon stock increased significantly during the 1980s and 1990s, and that a carbon sink of 58.4 ± 25.8 Tg C yr^{-1} and 92.2 ± 43.7 Tg C yr^{-1} was created during the 1980s and 1990s, respectively.

Many researchers have estimated changes in forest soil organic carbon (SOC). Using the rate of SOC change in European forests, Xie et al. (2007) estimated an increased SOC rate of 11.72 Tg C yr^{-1} from the 1980s to the 2000s. Based on a multiple regression equation of SOC, Piao et al. (2009) obtained the increased rate of 4.0 ± 4.1 Tg C yr^{-1} between 1982 and 1999. Using a biogeochemical model (InTEC), Wang et al. (2007b) showed that forest SOC increased at a rate of 7.84 Tg C yr^{-1} during 1950–1987 but considerably decreased at a rate of 61.54 Tg C yr^{-1} during 1988–2001. According to a model simulation, Chen et al. (2008) indicated that Chinese forest soils lost 6.0 Tg C yr^{-1} from 1982 to 2002. Using the forested area of 1.3×10^6 km^2 (mean of 1980–2000) and the change in SOC density, the SOC sequestration rate in China was estimated to be 4.7 ± 4.3 Tg C yr^{-1} (Huang et al., 2010b).

2.1.2 *Grassland*

Natural grassland in China occupies an area of $\sim4.00\times10^6$ km^2, accounting for 41.7% of the nation (State Environmental Protection Administration, 2007). Piao et al. (2009) estimated an increase of the grassland biomass stock by 7.0 ± 2.5 Tg C yr^{-1} during the 1980s and 1990s. However, the increasing grassland biomass may not contribute to a net long-term sink because carbon incorporated into plants is harvested in some grasslands and is released back as CO_2 into the atmosphere through the food web within the year. Likewise, using the multiple regression equation of SOC, Piao et al. (2009) estimated the increased SOC rate to be 6.0 ± 1.0 Tg C yr^{-1} between 1982 and 1999 in Chinese grassland (3.31×10^6 km^2). However, using a large number of field measurements, Yang et al. (2009, 2010) found no significant changes in SOC of northern grassland and Qinghai–Tibetan alpine grassland (a total of 1.96×10^6 km^2).

2.1.3 *Cropland*

China has $\sim1.3\times10^6$ km^2 of arable land. Fang et al. (2007) estimated that the cropland biomass stock increased by 13 Tg C yr^{-1} during the 1980s and 1990s. Similar to the grassland biomass, this sink does not contribute to a net long-term sink. Using the datasets obtained from 132 publications, Huang and Sun (2006) found that the SOC concentration increased in 53%–

59% of national croplands, in 30%–31% of national croplands SOC concentration decreased, and in 4%–6% of national croplands SOC concentration stabilized. They estimated that the cultivated layer (0–20 cm) of cropland soils sequestered 15–20 Tg C yr^{-1} between 1980 and 2000. If the soil layer was extended to ∼30 cm depth, the SOC sequestration rate was estimated to be 16.6–27.8 Tg C yr^{-1} over the same period (Sun et al., 2010). Recently, several researchers (e.g., Xie et al., 2007; Lu et al., 2009; Yu et al., 2009; Pan et al., 2010) also estimated the SOC sequestration rate in Chinese croplands, which is similar to the estimate by Huang and Sun (2006) and Sun et al. (2010). Based on the simulation of a biogeophysical model Agro-C (Huang et al., 2009b), it has been estimated that the croplands ($> 1.3\times10^6$ km^2) sequestered 25.2 Tg C yr^{-1} (range: 11.3–37.8 Tg C yr^{-1}) in the topsoil to 30 cm depth from 1980 to 2009 (Yu et al., 2012). Combining the estimates from various studies, the average rate of SOC sequestration in Chinese croplands (1.3×10^6 km^2) was estimated to be 21.7±4.3 Tg C yr^{-1} during this period (Huang et al., 2010b).

2.1.4 *Shrubland*

Shrubland in China covers $\sim2.0\times10^6$ km^2 (Fang et al., 2007; Piao et al., 2009). Research on the carbon balance of this important system has been very scarce. Using in situ biomass and satellite greenness information, Piao et al. (2009) estimated that shrubland was a net sink at the rates of 21.7±10.2 Tg C yr^{-1} in biomass and 39.4±9.0 Tg C yr^{-1} in the soils during 1982–1999. The increase in SOC of shrubland was higher than that of forest, grassland, and cropland. Notably, there exists large uncertainty in the SOC sink because the regression model used for estimating SOC was only able to interpret 33% of the observed SOC variation.

2.1.5 *Wetland and others*

Wetland in China covers $\sim0.659\times10^6$ km^2, excluding rivers and ponds. Marshland comprises the largest natural wetland, with an area of $\sim0.12\times10^6$ km^2 (China Wetland Resources Development and Environmental Protection Research Group, 1998). Using the datasets from the literature and from field measurements, Huang et al. (2010c) investigated the loss of SOC due to marshland conversion in Northeast China. They estimated that 0.0291×10^6 km^2 of marshland were converted to cropland over the period 1950–2000, and they pointed out that marshland conversion resulted in the SOC loss of 218–240 Tg C over a 50-year period (Huang et al., 2010c). In addition to the types of terrestrial ecosystems described here, bamboos were estimated to have accumulated 1.3 Tg C yr^{-1} during the 1990s (Pan et al., 2004). A small emission of 3.0 Tg C yr^{-1} due to forest fires was estimated (Lu et al., 2006).

2.1.6 *Emissions and uptake of methane*

Methane (CH_4) is the second largest radiative forcing gas after CO_2. Its global source strength has been slightly larger than its total sink strength since pre-industrial times, leading to increased atmospheric CH_4 concentrations. A combination of wetlands, rice paddies, and ruminants produces 50% of all methane; their microbial processes comprise >70% of microbial sources of methane, which account for ∼69% of all methane production (Conrad, 2009). The CH_4 emission fluxes from the different regions of China are quite divergent (Table 1). Based on the research done during 1995–2004, the annual budget of CH_4 emissions from natural wetlands and the spatio-temporal variations of CH_4 emissions in China were reviewed (Ding and Cai, 2007). Methane emission was 1.76 Tg CH_4 yr^{-1} from the natural wetland (a total of 94 000 km^2). Using observation data from 2002–2005, Song et al. (2009) estimated that in the Sanjiang Plain of Northeastern China, the annual mean CH_4 emission fluxes were 39.40±6.99 for permanently inundated wetlands, 4.36±1.79 for seasonally inundated wetlands, and 0.21±0.1 g cm^{-2} $yr^{-1}$for shrub swamps. If these results are scaled to the total research area (a total of 10 400 km^2), total CH_4 emission can be estimated at 0.24 Tg C yr^{-1}.

Rice paddies are a major source of anthropogenic terrestrial CH_4. Most recently, using a CH4MOD model, Zhang et al. (2011) estimated that an average of 6.62 Tg CH_4 yr^{-1} was released from irrigated rice cultivation (0.29×10^6 km^2) in China during the

Table 1. Emission fluxes of CH_4 in the different regions of China.

Region (Site)	Period	Emission flux (kg CH_4 hm^{-2} yr^{-1})	Land type	Reference
All country	1995–2004	187.2	Natural wetland	Ding and Cai (2007)
Sanjiang Plain	2002–2005	306.9	Wetland	Song et al. (2009)
All country	2005–2009	228.3	Irrigated rice cultivation	Zhang et al. (2011)
Xilin River basin	1995–2006	6.8	Wetlands and ruminants	Wang et al. (2009b)
Baiyinxile Livestock Farm	2004–2006	4.7–11.7	Semi-arid grassland	Liu et al. (2009)

period of 2005–2009. The source of ∼77% of the CH_4 emission was the rice region located at the mid-lower Yangtze River Valley and South China.

Wang et al. (2009a) studied the CH_4 budget in the Xilin River basin of Inner Mongolia. The basin area-weighted average from three processes (i.e., uptake by upland soils, emissions from wetlands, and ruminants) gave a total CH_4 emission from this basin (a total of 10 786 km^2) of 7.29 Gg CH_4 yr^{-1}. Liu et al. (2009) also found that the area of the Baiyinxile Livestock Farm of the Xilin River catchment in central Inner Mongolia, a managed semiarid grassland, did not serve as a terrestrial sink but as a source. The source strength amounted to 0.35–0.87 g C m^{-2} yr^{-1}. In the study of the effluxes of CO_2, N_2O, and CH_4 during the nongrowing season in four temperate forests in northeastern China, overall all forest soils were a sink of atmospheric CH_4 (Liu et al., 2010a). In addition, a high weighted mean methane flux rate of 15.1 mg CH_4 m^{-2} h^{-1} (ranging from −0.1 to 90 mg CH_4 m^{-2} h^{-1}) was found in the peak growing season of 2006 and 2007 in the littoral zones of Huahu Lake (a total of 1.6 km^2) (Chen et al., 2009). Analysis of long-term field observations from June 2003 to July 2006 shows that plants from alpine meadows contribute at least 0.13 Tg CH_4 yr^{-1} in the Tibetan Plateau (Cao et al., 2008). This finding further indicates that the assessment of methane emissions by plants is also important. Xie et al. (2010) discussed the debate related to the CH_4 emissions by plants.

Many different processes and environmental factors affect the emission and uptake of CH_4 in terrestrial ecosystems. The soils under different forest stands have different capacities to consume atmospheric CH_4. This ability is increased with the addition of extraneous carbon and is inhibited by the addition of N (Xu and Inubushi, 2007) and by the presence of ethylene (C_2H_4), which is easily produced under wet forest floors (Xu et al., 2008; Xu and Inubushi, 2009a). The change in temperature and soil pH can substantially affect the soil consumption of atmospheric CH_4 (Xu and Inubushi, 2009b). From an effective measurement of CH_4 production from temperate forest floors, Xu et al. (2008) concluded that the addition of N sources can induce a significant increase in the CH_4 production in situ.

Further and countinuous study of the production and consumption of CH_4 in typical forest stands in China under global change conditions is necessary.

2.2 *Impacts on carbon balance*

Using the inventory-satellite data method, Piao et al. (2009) reported the carbon sink rate of 177±73.4 Tg C yr^{-1} in the Chinese terrestrial ecosystems for the period 1980–1999. To verify these results and to take the other ecosystems into account, Piao et al. (2009) used an ensemble of atmospheric inversions and five process-based global ecosystem models to estimate the carbon balance and to quantify the effect of CO_2 and climate change on the carbon balance of China. Results from the process-based models and atmospheric inversions yielded a carbon sink rate of 173±39 Tg C yr^{-1} for the period 1980–2002 and 350±330 Tg C yr^{-1} for the period 1996–2005. After considering the "lateral fluxes," including emissions of non-CO_2 compounds and the oxidation of wood and food products, the sink from the inversion was reduced to 261 Tg C yr^{-1}. Thus, Piao et al. (2009) concluded a net carbon sink in the range of 0.19–0.26 Pg C yr^{-1}. Obviously, a large degree of uncertainty remains for the estimation of carbon sink in the Chinese ecosystems.

2.2.1 *Datasets and methods*

All estimates of carbon sinks in the terrestrial ecosystems rely on the observation datasets and methods used. Uncertainty in forest estimates mainly originate from forest inventory data and the chosen research method. An approach called biomass expansion factor (BEF) was used by Fang et al. (2007) and Piao et al. (2009) to estimate the forest biomass carbon storage. Although each set of parameter values was based on the field measurements for each forest type, error in the BEF model might be high for some particular provinces (Fang et al., 2007). In the estimate of grassland biomass used by Fang et al. (2007) (in addition to the grassland resource inventory), uncertainty mainly originated from remote sensing data and the estimation of belowground biomass. In these models, belowground biomass was simply estimated based on the ratio of belowground to aboveground biomass. A large degree of error (36%) for remote sensing data was reported by Fang et al. (2007). A relationship between vegetation productivity (NPP) and carbon sink for all vegetation types was used to derive the carbon sink of shrubland (Fang et al., 2007). An additional approach called "carbon sink efficiency" (CSE) was used in their study. Both methods actually rely on the estimate of NPP for forest and grassland, which obviously induces the large uncertainty.

In general, estimates of change in SOC usually use the measurements of SOC over a significant period (IPCC, 2006). Certainly, a sufficient number of measurement sites are required to reduce the uncertainty. The measured data of SOC in woodland and shrubland in the 2000s are rather deficient in China. Hence, a degree of error has been introduced into the observation-based estimates. Currently, models are widely used to estimate the terrestrial carbon budget on regional and global scales, but the validity of the models, utility of model input parameters, and upscaling processes may restrict the accuracy of the estimates (Huang et al., 2008). Regression models used in Piao et al. (2009) can only explain 23%–53% of the variation in the observation values for SOC storage (Huang et al., 2010b). The use of these models to estimate SOC inherently includes a large degree of uncertainty. Thus, the model results from five global ecosystem models were not taken as "best estimates" (Piao et al., 2009), because none of the models explicitly considered changes in land use and land management. Furthermore, the models were not carefully validated in particular regions of China, including the simulation of climate change. Although the atmospheric inversion method is very useful, the uncertainty therein is generally large because many errors are introduced into the estimate: atmospheric network stations are scarce, transport model errors are sensitive, and fossil-fuel emissions are based on estimates (Piao et al., 2009).

2.2.2 *Land-use change*

Land-use change has an important role in terrestrial carbon cycling. Conversion of one land use to another probably alters carbon storage. Many researchers have estimated that vegetation and soil C are increased when cropland is converted to forest, i.e., when afforestation and reforestation are implemented (Fang et al., 2001; Xie et al., 2008; Zhang et al., 2008; Huang et al., 2009a). According to Fang et al. (2007), the forest (defined as 20% canopy coverage) area of 11×10^4 km^2 in China increased between the periods of 1989–1993 and 1999–2003. This estimate is different from the one given by Liu et al. (2004), who reported that the forest and grassland areas decreased by 1.0×10^4 km^2 and 3.35×10^4 km^2, respectively but that cropland area increased by 4.05×10^4 km^2 between 1990 and 2000. A continuous increase in the forest carbon biomass is expected because of the increase of forest area and forest regrowth in the future (Fang et al., 2007). Carbon can accumulate at a rate of 61 g C m^{-2} in the soil of the old growth forest (stand age >400 years) in South China (Zhou et al., 2006). Related studies have mostly focused on the change in topsoil organic C sequestration rather than deep soil. Field and laboratory measurements show that extraneous disturbances, such as N addition, can affect the mineralization of "old carbon" in deep soils under temperate old-growth forests in Northeast China (Xu et al., 2009a). Hence, the carbon dynamic in deep soils and its response to extraneous disturbances should be taken into account when estimating C sequestration.

Forestated area has greatly increased in China in the last three decades. It has been reported that the area of shelter trees increased by 53×10^4 km^2 from 1978 to 2007 (National Bureau of Statistics of China, 2009). During the period 2003–2007, the plantations of shelter trees accounted for 73% of national afforestation (Huang et al., 2010b), which increases the biomass stock and also affects the carbon storage in the soil.

2.2.3 *Grassland management*

Grazing is a significant factor influencing the grassland system. Based on statistical data, Huang et al. (2010b) determined that 204 counties out of 266 semi-pastoral and semi-agricultural regions were overgrazed. The degradation rate of grassland was estimated at 1.3×10^4 km^2 yr^{-1} in the late 1980s and at 2.0×10^4 km^2 yr^{-1} in the early 2000s. Therefore, $\sim$90% of the natural grassland in China has degraded to some degree (State Environmental Protection Administration, 2009). Du (2006) estimated that in the major pastoral region of North China in the mid-1980s, degraded grassland made up 39.7% of the total available grassland and that this amount increased to 50.2% in the mid-1990s.

Grassland degradation decreases SOC stocks (Zou et al., 2007). An analysis of the literature shows a decrease in SOC stocks by 27%–55% in degraded pastures, compared to non-degraded pastures (Huang et al., 2010b). SOC stocks significantly decline with increasing grazing intensity (Dong et al., 2007; Qiu et al., 2007; Wang et al., 2007a). Huang et al. (2010b) estimated that SOC stocks were lower than those in non-grazing pastures in the lightly grazed pastures by 30%±12%, in moderately grazed pastures by 35%±14%, and in heavily grazed pastures by 50%±15%. Enclosures have an important role in the degraded grasslands (Xue et al., 2008; Pei et al., 2008; He et al., 2008; Jia et al., 2009). SOC can increase by an estimated 28% after 20 years of enclosure and by 160% after 14–23 of vegetation restoration and by 450% after 40–50 years of vegetation restoration, respectively, compared with the initial 0–4 years (Huang et al., 2010b). In a meta-analysis by Shi et al. (2009), losses of SOC in the grassland with various grazing intensities exceeded the SOC increase in enclosure and grazing forbidden grassland.

2.2.4 *Climate change and others*

Climate change is one of the most important factors influencing the carbon balance. Precipitation is a particularly important driver for vegetation growth. Studies have shown that summer precipitation in China has significantly increased, which may have benefited vegetation growth (Fang et al., 2004). Temperature and soil properties affect the function of SOC sequestration and microbial carbon utilization of carbon (Xu et al., 2006b, 2007a). Recent studies have shown that microbial biomass carbon concentrations and metabolic quotients of the soils are useful parameters for studying soil carbon availability and soil carbon sequestration (Xu et al., 2007a).

Urbanization in China has resulted in the migration of a large rural population into cities, which has induced many ecological alterations. A change in energy use is one of these changes. In the past 30 years, firewood, charcoal, and crop straw that had been used as major energy supplies in most areas have been steadily replaced by fossil fuel. This transition has decreased the collection of fuel wood, which has led to the recovery of shrublands and has increased fossil fuel emissions (Piao et al., 2009).

Because crop production significantly increased between 1950 and 1999 (Huang et al., 2007), the amount of residue and root input into the soil also increased. Recent agriculture practices decrease removal of crop residues as reduced and zero tillage practices expand, which is likely to increase the carbon sink in the cropland (Piao et al., 2009). Meanwhile, this type of agriculture practice eventually increases SOC. Generally, the estimates of SOC change are based on surface soil layers. However, some studies (Gu et al., 2004; Wang et al., 2007c; Pan et al., 2008) suggest the SOC accumulation in deep soil layers, implying that the SOC accumulation in China has been underestimated.

2.3 *Nitrogen cycle*

Natural nitrogen (N) is continuously cycled through many different processes: lightning, biological nitrogen fixation, nitrification, and denitrification are some examples. Therefore, biological fixation, atmospheric emission, and deposition generally maintain the nitrogen balance. Two anthropogenic activities have considerably increased reactive nitrogen: the development of intensive agriculture and a rapid growth in energy consumption. To meet food production and other industrial activities, anthropogenic nitrogen fertilizers (i.e., ammonia) were created, whereas the increase in energy production by burning fossil fuels mainly generates nitrogen oxides that are converted to different nitrogen forms in the atmosphere. In addition, agriculture practices in some East Asian countries have changed. High-input systems with greater use of nitrogen fertilizer and production of higher numbers of animals have been employed. Changing lifestyles and farming patterns substantially affect the balance of material cycles, including those of carbon and nitrogen. As a result, more and more reactive nitrogen in both reduced and oxidized forms is being emitted into the atmosphere and redeposited onto the surfaces of terrestrial and marine ecosystems. As a result of these processes, a particularly important gas, N_2O, is produced, and its concentration in the atmosphere has increased.

2.3.1 *Nitrogen budget*

A number of studies have focused on the different aspects of nitrogen budget in China. Table 2 shows the nitrogen balance in the some regions of China. Using China's county-level agricultural database of 1980 and 1990, Bao et al. (2006) studied the fate of the large amounts of nitrogen (N) brought into the agricultural environment by human activities in the Yangtze (Changjiang) River basin. Results show that anthropogenic reactive N exceeded the terrestrial bio-fixed N, and human activities significantly altered the N cycle in this region. The total inputs of N in 1980 and 1990 were 8.0 and 12.9 Tg N, respectively, whereas the total N outputs were 4.41 Tg N in 1980 and 6.85 Tg N in 1990. Thus, the excess N that was stored in farmland was 1.51 Tg N in 1980 and 2.67 Tg N in 1990, and losses through transport to water bodies were 2.08 Tg N in 1980 and 3.38 Tg N in 1990. Deng et al. (2007) also studied the N budget of the Yangtze River delta region and evaluated the effect of the human-altered nitrogen cycle on the environment. They concluded that the total nitrogen input to the region was 2.94 Tg in 2002, and the average nitrogen input per unit area was 291 kg hm^{-2} yr^{-1}, which is 4.5 times the average national level. Nitrogen flux on land reached 224 kg hm^{-2} yr^{-1}, defined as nitrogen use in fertilizer plus livestock and human waste per unit area. Most of the nitrogen input was associated with agriculture. Total nitrogen output from the region was $\sim$1.66–1.95 Tg yr^{-1}, resulting in a nitrogen surplus of $\sim$0.99–1.28 Tg yr^{-1} that was probably stored in farmland and water bodies. The nitrogen surplus was probably overestimated because the output through the land-use change and denitrification in the underground water was not taken into account (Deng et al., 2007). The nitrogen surplus of Deng et al. (2007) is smaller than the esti-

Table 2. Nitrogen budgets in some regions of China.

Region	Inputs (Tg N)	Outputs (Tg N)	Surplus (Tg N)	Time	Reference
Yangtze River Basin	8.00	4.41	3.59	1980	Bao et al. (2006)
	12.9	6.85	6.05	1990	
Yangtze River delta region	2.94	1.66–1.95	0.99–1.28	2002	Deng et al. (2007)
Greater Hangzhou Area	0.275	0.227	0.048	2004	Gu et al. (2009)

mate by Bao et al. (2006), but the area calculated in Deng et al. (2007) is much smaller than that used in Bao et al. (2006).

Using the mass balance approach, Gu et al. (2009) studied the N cycling in an urban–rural complex system called the Greater Hangzhou Area (GHA; 1.66×10^4 km^2). Results showed that total N input into the GHA was at 274.66 Gg yr^{-1} in 2004 and that total output was at 227.33 Gg yr^{-1}, indicating that N was accumulated at 47.33 Gg yr^{-1}. Therefore, nitrogen input to and output from the GHA were increased by 130% and 131%, respectively, compared with the amounts in 1980. Human activities resulted in 73% of N input by means of synthetic fertilizers, human food, animal feed, imported N containing chemicals, fossil fuel combustion, and other items. More than 69.3% of N was released into the atmosphere, and riverine N export accounted for 22.2% of total N output.

Based on a dataset of 2480 soil profiles and a map of Chinese soil types, Tian et al. (2006) investigated the storage and spatial distribution of soil nitrogen in China. Results showed that the total N storage in China was 8.29 Pg in the 1990s, representing 5.9%–8.7% of the total global N storage. Nitrogen density varied substantially with soil types and regions. Peat soils in southeastern Tibet and Southwest China, showed the highest mean N density (7314.9 g m^{-3}) among all soil types. This value was >30 times the lowest N density of brown desert soils in the western desert and arid region. N density also varied with land cover types in China. Wetlands in Southwest China exhibited the highest N density (6775.9 g m^{-3}) and deserts in Northwest China had the least (447.5 g m^{-3}).

Using a compartment model, Sun and Liu (2007) studied the nitrogen distribution and cycling of atmosphere–plant–soil system in the typical meadow *Calamagrostis angustifolia* wetland (TMCW) and marsh meadow *Calamagrostis angustifolia* wetland (MMCW) in the Sanjiang plain. They reported that the N wet deposition was 0.757 g N m^{-2} yr^{-1}, of which total inorganic N accounted for 85%. The ammonia volatilization amount in TMCW and in MMCW soils in the growing season was 0.635 and 0.687 g N m^{-2}. The denitrification gaseous loss amount was 0.617 g N m^{-2} in TMCW soils in the growing season and 0.405 g N m^{-2} in MMCW soils. Soil organic N was 93.98% of total nitrogen in TMCW soils and 92.16% of total nitrogen in MMCW soils in these two plant–soil systems.

Ju et al. (2006) studied the annual N budget and groundwater nitrate-N concentrations in the field in three major intensive cropping systems of wheat–maize rotations, greenhouse vegetable, and apple orchards in Shandong Province, North China. Nitrate leaching was evident in all three cropping systems, and the groundwater in shallow wells (<15 m depth) was heavily contaminated in the greenhouse vegetable production area, where total nitrogen inputs were much higher than crop requirements and the excessive fertilizer nitrogen inputs were only ∼40% of total nitrogen inputs.

2.3.2 *Atmospheric deposition*

Atmospheric nitrogen deposition refers to the process whereby airborne nitrogenous compounds, including inorganic nitrogen, organic nitrogen, and particulate nitrogen are deposited on the Earth's surface by wet deposition and/or dry deposition. However, long-term atmospheric deposition of inorganic nitrogen can affect the nitrogen balance, which probably results in some negative effects on terrestrial ecosystems such as soil acidification, nutrient imbalance, losses of plant community diversity, increased susceptibility to environmental stresses. The deposited nitrogen actually comes from the atmospheric nitrogen emission, including the emissions from the terrestrial ecosystems and the ocean.

Zhang et al. (2006) established a monitoring network of nine sites to study the spatial and temporal variation of atmospheric nitrogen deposition in the North China Plain (NCP) over a 2-year period. The annual bulk deposition of inorganic nitrogen in the North China Plain ranged from 18.4 kg hm^{-2} to 38.5 kg hm^{-2}, with an average of 28.0 kg hm^{-2}. Annual bulk deposition of inorganic nitrogen in the Beijing area (32.5 kg hm^{-2}) was higher than that in Shandong and Hebei provinces (21.2 kg hm^{-2}). A significant spatial variation of bulk deposition occurred in the Beijing area, and 60% of the bulk deposition occurred from June to September. These results suggest that reduced nitrogen in precipitation was dominant in rural regions, whereas oxidized N from precipitation was a major form in urban regions. Wet N deposition made up 73% of the bulk deposition, implying that dry N deposition was important in the North China Plain.

Fan et al. (2009) conducted a 2-year monitoring study to estimate nitrogen deposition in a typical red soil forestland in Southeast China. The total inorganic nitrogen deposition was 83.7 kg hm^{-2} yr^{-1} in 2004 and 81.3 kg hm^{-2} yr^{-1} in 2005. The dry deposition accounted for 78.6% of total nitrogen deposition, in which ammonia contributed 86.1%. Their results showed that intensive agricultural practices such as excessive nitrogen fertilization and livestock production were responsible for atmospheric inorganic nitrogen. He et al. (2010) also monitored total N deposition at two locations, Dongbeiwang near Beijing and Quzhou in Hebei province, over a 2-year period from 2005 to 2007 using an ^{15}N tracer method and the integrated total N input (ITNI) system, respectively. Their results showed that total airborne N inputs to a maize–wheat rotation system at both locations ranged from 99 to 117 kg N hm^{-2} yr^{-1}, with higher N deposition during the maize season (57–66 kg N hm^{-2}) than the wheat season (42–51 kg N hm^{-2}). Their results are much higher than those obtained by Zhang et al. (2006) using the bulk method.

Zhang et al. (2008) have reviewed the effects of N deposition on the fluxes of greenhouse gases from forest soils. The effects of N deposition on greenhouse gas fluxes from forest soils depend on forest type, N status of the soil, and rate of N deposition. In forest ecosystems where biological processes were generally limited by N supply, N additions either stimulated soil respiration or had no significant effects, whereas in "N saturated" forest ecosystems, N additions decreased CO_2 emissions, reduced CH_4 oxidation, and increased N_2O fluxes from the soil. The change in greenhouse gas fluxes from the soil is also related to the status of soil-available carbon and its interaction with N turnover in soil. In a comparison of three temperate forests dominated with *Pinus sylvestris* L., *Cryptomeria japonica* and *Quercus serrata*, respectively, the smallest effective concentration of the added nitrate inhibited CH_4 consumption in the *Pinus* forest soil (Xu and Inubushi, 2007). Concentrations of soil-available carbon and glucose addition remarkably affected the uptake of atmospheric CH_4 by soil (Xu and Inubushi, 2007).

2.3.3 *Atmospheric emissions*

The nitrogen emitted to the atmosphere is mainly N_2O, NH_3, and NO_x. Xiong et al. (2008) analyzed the impacts of population growth, food preferences and agriculture practices on the nitrogen cycling in East Asia. In China, fertilizer nitrogen input increased from 0.54 Tg in 1961 to 28 Tg in 2005, and the animal population also increased dramatically, from 27 million to 1 billion. As a result, 13 Tg N was lost to the environment in 2005 as nitrous oxide, ammonia, or nitrate. They estimated that China emitted 1.05 Tg N of N_2O and 9.42 Tg N of NH_3 to the atmosphere in 2004. He et al. (2010) estimated that in China, NH_3 and NO_x emissions were as high as 10.4 Tg NH_3-N and 3.4 Tg NO_2-N in 2000, derived mainly from agricultural activities and industrial emissions (including transportation and power plants), respectively.

Zou et al. (2009) investigated nitrogen fertilizer-induced direct nitrous oxide (N_2O) emissions during the rice-growing season in mainland China between the 1950s and the 1990s. The results showed that total nitrogen input during the rice-growing season increased from 87.5 kg N hm^{-2} in the 1950s to 224.6 kg N hm^{-2} in the 1990s, and that seasonal N_2O emissions increased from 9.6 Gg N_2O–N yr^{-1} in the 1950s to 32.3 Gg N_2O–N yr^{-1} in the 1990s. In the 1990s, N_2O emissions during the rice-growing season made up 8%–11% of the reported annual total of N_2O emissions from croplands in China. Zou et al. (2010) further estimated annual synthetic fertilizer N-induced direct N_2O emissions (FIE-N_2O) from Chinese croplands during 1980–2000. Annual FIE-N_2O was estimated to be 115.7 Gg N_2O–N yr^{-1} in the 1980s and 210.5 Gg N_2O–N yr^{-1} in the 1990s. Upland croplands contributed most to the national total of FIE-N_2O, accounting for 79% in 1980 and 92% in 2000.

Wolf et al. (2010) reported year-round N_2O flux measurements with high and low temporal resolution at 10 steppe grassland sites in Inner Mongolia, China. Short-lived pulses of N_2O emission during spring thaw dominated the annual N_2O budget. The N_2O emission pulses were highest in ungrazed steppe regions and decreased with increasing stocking rate, suggesting that grazing decreased rather than increased N_2O emissions. They also pointed out that by neglecting these freeze–thaw interactions, existing approaches may have systematically overestimated N_2O emissions over the last century for semi-arid, cool temperate grasslands by up to 72%.

Improving nitrogen-use efficiency (NUE) to 40% in cropland could cut 4.4 million tons of synthetic N use per year (Huang and Tang, 2010). As a result of this reduction, direct N_2O emission from croplands together with CO_2 emission from industrial production and transport of synthetic N could be reduced by 27%, equivalent to 40 Tg CO_2_eq yr^{-1}. Therefore, improving N management could greatly reduce GHG (N_2O and CO_2) emissions in Chinese croplands. Using datasets from the literature and field measurements, Huang et al. (2010c) estimated that marshland conversion to cropland in Northeast China over the period 1950–2000 reduced CH_4 emissions from the former marshland by a cumulative amount of ~28 Tg relative to 1950. Taking the loss of SOC and emissions of CH_4 and N_2O into account, the integrated global warming potential in the 1990s, compared with the 1950s, was reduced by 21%–33% due to marshland conversion in Northeast China (Huang et al., 2010c).

Zhou et al. (2010) developed a process-based site model to simulate daily N_2O emission from a rice-winter wheat rotation cropping system. The 3-year observations conducted in East China were used to examine the model. The simulated results reflected the interannual variation of N_2O emissions. Sensitivity analyses indicated that the simulated N_2O emission was most sensitive to the fertilizer application rate and the soil organic matter content, but N_2O emission was much less sensitive to variations in soil pH and texture, temperature, precipitation, and crop residue incorporation rate under local conditions. These results suggest that further calibration and validation are required to apply the model in the other regions.

3. Marine carbon and nitrogen cycles

The oceans contain the largest carbon and reactive nitrogen sources among three reservoirs, and they have the capacity for absorbing and retaining CO_2. Hence, the oceans play a very important role in the global carbon and nitrogen cycles. Research on the sink and source of both carbon and nitrogen as well as their biogeochemical processes in the ocean can help us to understand the global budget and transport of both carbon and nitrogen in the future, and to project the change of atmospheric CO_2.

3.1 *Carbon cycle in the ocean margins*

Rivers play an important role in the transport and transformation of carbon from the land to the ocean. Approximately 1 Pg of carbon is discharged annually from the land to the ocean through rivers and estuaries (Guo et al., 2008). In addition to estuaries and marshes, coastal waters, despite comprising only a small portion of the world's ocean surface area, play a critically important role in the global oceanic carbon cycle and have recently received increasing attention (Cai et al., 2006; Zhai and Dai, 2009). Some researchers have estimated that continental shelves may absorb atmospheric CO_2 at a rate up to 1 Pg C yr^{-1}, or 50% of known open ocean uptake (Cai et al., 2006). Cai et al. (2006) argued that the estimated carbon uptake rate in the ocean margins was based on data from a single type of shelf located in the northern temperate zone near populated areas. Therefore, a large degree of uncertainty exists for the estimate of carbon uptake in the ocean margins, making it difficult to balance the global CO_2 budget. In the past 4 years, many studies concerning the carbon cycle in the ocean margins, especially in the estuaries and shelf of China, have been made by Chinese scientists.

3.1.1 *Carbon fluxes to the ocean from rivers*

Shelves are an important area for the connection of rivers and oceans. Based on circulation and latitude, Cai et al. (2006) divided the highly heterogeneous shelves into seven provinces in terms of distinct physical and biological characteristics to estimate the shelf atmosphere–ocean CO_2 flux. The continental shelves were a sink for atmospheric CO_2 at mid-high latitudes (-0.33 Pg C yr^{-1}) and a source of CO_2 at low latitudes (0.11 Pg C yr^{-1}). Warm temperature and high terrestrial organic carbon inputs were most likely responsible for the CO_2 release in low latitude shelves. A strong correlation was revealed between specific HCO_3^- fluxes and discharge in all four rivers (Yangtze, Huanghe, Pearl, and Mississippi rivers, respectively) with different discharge seasonality, implying that higher precipitation in drainage basins can promote higher weathering rates (Cai et al., 2008). Among the 25 largest rivers in the world, the rivers in low latitudes accounted for 42.6% of the total global dissolved inorganic carbon flux to the ocean, middle latitudes accounted for 47.3%, and high latitudes accounted for 10.1%. Rivers in middle latitudes carried a disproportionally high dissolved inorganic carbon flux to the ocean within a relatively small (26%) amount of freshwater discharge (Cai et al., 2008).

Among the rivers at middle and high latitudes are the largest Asian river (Yangtze River) and other important rivers (e.g., Huanghe, Zhujiang Rivers) in China. In the study of the inorganic carbon in offshore sediments of the Yangtze River Estuary and Jiaozhou Bay, sequential extraction was used to divide inorganic carbon into five forms (NaCl, $NH_3.H_2O$, NaOH, $NH_2OH.HCl$, and HCl), and the HCl form might be one of end results of atmospheric CO_2 (Li et al., 2006a). Li et al. (2006a) suggested that Yangtze River estuary sediments absorb at least $\sim$4.1 Tg of atmospheric CO_2 every year, which indicates that offshore sediments play an important role in absorbing atmospheric CO_2. Based on the data from a cruise in the Pearl River estuary in April 2007 along a salinity gradient, He et al. (2010) investigated the distribution, degradation, and dynamics of organic carbon and its major compound classes, including carbohydrates and amino acids. Their study indicated that anthropogenic sewage input appeared to be an important source of the DOC pool in the upper estuary, and that 5.3×10^8 g C d^{-1} of DOC could be exported out from the Lingdingyang Bay (a major subestuary of the Pearl River estuary) to the continental shelf of the South China Sea during the low-flow season.

3.1.2 *Seasonal variations of the carbon cycle*

Zhai et al. (2007) examined the carbonate system using the data from four field surveys. Together with previously reported data, their study provided full-season coverage of CO_2 outgassing fluxes in the Yangtze River Estuary system. Surface pCO_2 ranged from 65 to 144 Pa in the upper reaches of the Yangtze River Estuary, 100–460 Pa in the Huangpujiang River, and 20–100 Pa in the estuarine mixing zone. The CO_2 emission flux from the main stream of the Yangtze Estuary was at a low level, 15.5–34.2 mol m^{-2} yr^{-1}. They estimated that including the Huangpujiang River and the adjacent Shanghai inland waters, CO_2 degassing flux from the Yangtze Estuary may represent only 2.0%–4.6% of the DIC exported from the Yangtze River into the East China Sea. Based upon more data of seven field surveys conducted during April 2005–April 2008, Zhai and Dai (2009) studied the seasonal variation of air-sea CO_2 fluxes in the outer Yangtze Estuary and on the inner shelf of the East China Sea (ECS). An obvious seasonal variation of surface pCO_2 was observed in this most dynamic zone of the ECS. The outer Yangtze Estuary served as a moderate or significant sink of atmospheric CO_2 in winter, spring, and summer, while it turned to a net source in autumn. The seasonal variation appeared to be controlled by primary productivity and air-sea exchange in the warm seasons and by mixing in the cold seasons.

Based on data from five surveys, Guo et al. (2008) examined the seasonal variation of the inorganic carbon system in the Pearl River Estuary. Both DIC and total alkalinity (TA) values in the freshwater endmembers were considerably higher in the dry season (>2700 μmol kg^{-1} for DIC and >2400 μmol kg^{-1} for TA) than in the wet season (~1000 and 700 μmol kg^{-1} for DIC and TA); however, riverine DIC flux and drainage basin weathering rates, were significantly higher in the wet season (611×10^9 mol yr^{-1} and 13.6×10^5 mol km^{-2} yr^{-1}) than in the dry season (237×10^9 mol yr^{-1} and 5.3×10^5 mol km^{-2} yr^{-1}). The complex behaviors of DIC and TA in the estuarine mixing zone were mainly a result of mixing between tributaries, with distinct and seasonally variable DIC and TA values. Liu et al. (2010b) evaluated the seasonal cycle and effect of phosphorus on the plankton ecosystem in the waters of the Pearl River Estuary. They found that the available water volume for phytoplankton photosynthesis changed seasonally, and primary productivity varied from ~36 kg d^{-1} in the dry season to ~31 kg d^{-1} in the wet season.

3.1.3 *Phytoplankton structure in the ocean margins*

The phytoplankton structure and nutrients in cultural areas and aquaculture areas of Daya Bay, South China Sea, were examined by Wang et al. (2006 and 2009b). Appropriate water temperature, salinity, sufficient dissolved silicate (DSi), as well as quick recovery of nutrients, played important roles in the high abundance of phytoplankton and frequent outbreak of blooms in the cultural areas of Daya Bay (Wang et al., 2006). A survey in the aquaculture areas of Daya Bay showed that diatoms were the dominant phytoplankton group, accounting for 93.21% of the total abundance and dissolved inorganic phosphorus (DIP), the most necessary element for phytoplankton growth. Dinoflagellates comprised the second most abundant group (Wang et al., 2009b). In addition to Daya Bay, Dai et al. (2008) observed a phytoplankton bloom downstream of a large estuarine plume in the Pearl River Estuary and the northern South China Sea in May–June 2001. A cascade of changes during the bloom event demonstrated enhanced photosynthesis during the bloom: a significant shift of the surface water phytoplankton community structure from a picophytoplankton dominated community to one dominated by microphytoplankton; a significant drawdown of pCO_2; a biological uptake of DIC; and an associated enhancement of dissolved oxygen and pH. Huang et al. (2010a) examined the phytoplankton community at two warm eddies in the northern South China Sea in winter 2003/2004; phytoplankton communities observed in these two eddies were significantly different. In one warm eddy, the phytoplankton community was dominated by prochlorophyceae within the euphotic zone, whereas in the other warm eddy, haptophyceae was dominant in the euphotic zone. They pointed out that the difference in the phytoplankton community was due to the different origins and ages of the two warm eddies. The carbon fixed by phytoplankton and cultured algae has been discussed by Song et al. (2008) based on *in situ* investigation and data analysis in China coastal seas. The carbon fixed by phytoplankton was ~2.22×10^{11} kg yr^{-1} with a clear seasonal variation in the Bohai Sea, the Yellow Sea, and the East China Sea, while carbon fixed by phytoplankton was ~4.16×10^{11} kg yr^{-1} in the South China Sea. In addition, an adjoint data assimilation method was applied in a coupled physical–biological model of the Bohai Sea and the Yellow Sea (BYS) by Zhao and Lu (2008) to estimate the ecological parameters. Phytoplankton data were the strongest constraints during the parameter estimation process, and the simulated horizontal distributions of surface phytoplankton were consistent with the biological roles of seasonal stratification.

3.2 *Carbon cycle in the open ocean*

As mentioned in the previous section, there is still some controversy over the exact figure of carbon uptake in the ocean and its future changes. For the calculation of air-sea CO_2 exchange fluxes, under the same wind speed, different formulae can lead to a difference of up to several tens of percent in the exchange coefficient, and use of different formulae of thermodynamic constants may generate a difference of up to 3 Pa in the calculated partial pressure of CO_2 at surface water (Xu et al., 2004). Many other parameters are involved in the estimation of ocean carbon uptake and storage. The processes may vary among the different regions of the expansive global oceans. Even for the same process, the parameters are often region-dependent; for example, the transport coefficients of carbon in the interior ocean.

The study of carbon cycle in the ocean basins can be performed with the observation data and the models. In the summers of 1999 and 2003, the partial pressure of CO_2 in the air and surface waters (pCO_2) of the Bering Sea and the western Arctic Ocean were measured by the First and Second Chinese National Arctic Research Expeditions (Chen and Gao, 2007). Using these data, Chen and Gao (2007) found that the surface pCO_2 values gradually increased from the continental shelf waters, the Bering Sea shelf slope, to the Bering Abyssal Plain (BAP), and the Canadian Basin. The difference was attributed to the combination of various source waters, biological uptake, and seasonal warming. Results showed that Chukchi Sea was a carbon sink. They also found that SST and primary production affected the seasonal variation of surface pCO_2.

Over the past 4 years, some modeling studies about the ocean carbon cycle and some related work have been produced by Chinese scientists, including the model assessment with passive tracers such as CFCs, ^3H, and ^{14}C (e.g., Xu et al., 2006c; Li et al., 2006b; Chu et al., 2008; Ba and Xu, 2010) and the examination of transport coefficients (e.g., Xu et al., 2006c; Li et al., 2007). These studies suggest that the performance with isopycnal parameterization of transport of tracers has been generally improved in the ocean general circulation model (OGCM) of the North Pacific and of the global ocean (L30T63 developed by the LASG/Institute of Atmospheric Physics), relative to the traditional horizontal diffusion mixing scheme of tracers. A gradient of tracer inventories from west to east in the middle latitudes of the North Pacific has been well simulated under the condition of relatively large isopycnal diffusivity. Based on these works, the carbon cycle in the both basin and global oceans, especially in the Pacific Ocean, has been simulated.

Xu et al. (2007b) used a basin-wide OGCM of the North Pacific with the open southern boundary condition to study the uptake and distribution of anthropogenic CO_2 in the North Pacific. Larger isopycnal diffusivity produced larger exchange fluxes of anthropogenic CO_2 in the western North Pacific but smaller fluxes in the equatorial region, and during the period 1800–1997, the North Pacific took up 23.75 Pg C of anthropogenic CO_2. The same model with the rigid southern boundary condition was used to identify locations that exhibited more efficient for ocean CO_2 disposal in the North Pacific (Xu et al., 2009b). Four injection depths at each of 15 locations were chosen, and the simulated results showed that the sequestration was more efficient for the injection in the east than in the west. Xu and Li (2009) used a global OGCM called L30T63 to study the uptake and distribution of anthropogenic CO_2 in the ocean. Two runs with different isopycnal diffusivities estimated that the global oceanic anthropogenic CO_2 uptake rates were 1.64 and 1.73 Pg C yr^{-1} for the 1990s. The use of large isopycnal diffusivity generally improved the simulated results, including the exchange flux, the vertical distribution patterns, and storage.

3.3 *Nitrogen cycle in ocean margins*

Nitrogen plays an essential role in the life activity in the ocean. Phytoplankton take up CO_2 and nutrients in the presence of light through the photosynthesis. The most common nitrogen compounds are nitrate and ammonium. These inorganic nitrogen compounds are transformed into organic nitrogen through different chemical and biological processes in the ocean. Certainly, organic nitrogen can also be transformed into inorganic nitrogen. In addition, organic nitrogen can probably be used by some species directly. Both riverine nitrogen input and atmospheric nitrogen deposition are thought to alter the nitrogen and carbon cycles in the ocean, which may affect primary productivity and even change ecosystem composition or function. Therefore, studies of both atmospheric inorganic and organic deposition are important for understanding carbon and nitrogen cycles as well as future climate change.

Shi et al. (2006) reviewed recent studies of atmospheric deposition of organic nitrogen. Organic nitrogen accounted for 39.6% $\pm$14.7% of total aerosol nitrogen. In rainwater from continental locations, 30.2% $\pm$15.0% of dissolved nitrogen was present in organic forms, whereas in remote marine rains organic nitrogen was 62.8% $\pm$3.3% of total nitrogen. Atmospheric nitrogen deposition to the world's ocean may be important, if organic nitrogen is taken into account (Shi et al., 2006).

Although atmospheric N_2O concentration is three orders of magnitude lower than that of CO_2, N_2O has a per molecule radiative forcing strength 200–300 times greater than CO_2, and its greenhouse effect cannot be ignored. A review of research published on the biogeochemical cycle of nitrous oxide in the oceans for the past several decades was made by Zhan and Chen (2006), in which the vertical distribution of N_2O in the oceans, its impact factors as well as formation and removal mechanisms were discussed in more detail. Using the measured data of N_2O concentrations, which were collected along cruise tracks between 30°–67°S and in Prydz Bay, Antarctica, in the 22nd Chinese National Antarctic Research Expedition (November 2005 to March 2006), Zhan and Chen (2009) showed that the N_2O concentration in surface seawater increased from 8.9±0.2 nM to 17.9±0.3 nM along the cruise tracks southward from 30°–67°S latitude and was well correlated with SST. They pointed out that distributions of SST inducted the negative saturation anomaly south of the Subantarctic Front and positive saturation anomaly north of the Subantarctic Front, leading to the positive and almost zero air-sea fluxes in these two regions, respectively.

Ammonia-oxidizing archaea (AOA) have recently been found to be potentially important in nitrogen cycling in a variety of environments, especially in estuaries (Dang et al., 2008). The spatial distribution of putative soil-related AOA in certain sampling stations showed that the Yangtze freshwater discharge strongly affected the marine benthic microbial ecosystem. The transport of terrestrial archaea into seawater and sediment might be attributed to nutrients, organic matter, suspended particles, and the diluted water of the Yangtze River, in addition to freshwater (Dang et al., 2008).

4. Carbon–nitrogen cycle and climate change

Climate change in the future will greatly depend on the anthropogenic emissions of greenhouse gases, particularly CO_2. The positive feedbacks between climate change and the carbon cycle have been noted; they indicate that climate warming causes the reduction of carbon uptake in the terrestrial ecosystem and oceans. Carbon uptake in the both land ecosystems and oceans is generally limited by the availability of nutrients. Nitrogen in the land ecosystems is quite sensitive to human activities, including fertilization and land-use changes. As mentioned above, atmospheric nitrogen deposition has been increasing because of accelerating industrialization and use of nitrogen fertilizer, which will probably affect regional and global carbon budgets and regulate the response and feedback of the biosphere to climate change. For projection of climate-carbon feedbacks, one of the largest uncertainties comes from the estimate of the carbon sequestration potential in terrestrial ecosystems. However, in the early studies, nitrogen limitation to terrestrial carbon sequestration is generally not included in the model. Therefore, understanding the interaction between nitrogen and carbon cycling is very important.

4.1 *Nitrogen impacts*

The increase in atmospheric CO_2 can stimulate terrestrial C sequestration, which is related to nitrogen availability. To investigate the responses of terrestrial plant species under global nitrogen enrichment, Xia and Wan (2008) conducted a meta-analysis of data from 304 studies to reveal the general response patterns of terrestrial plant species to the addition of nitrogen. Across 456 terrestrial plant species included in the analysis, under nitrogen enrichment, biomass and nitrogen concentrations increased by 53.6% and 28.5%, respectively, and nitrogen responses depended on plant functional types, with significantly greater biomass increases in herbaceous than in woody species.

Xia et al. (2009) conducted a field manipulative experiment of warming and nitrogen addition in a temperate steppe in the semiarid grassland of Duolun County, Inner Mongolia, China, during two contrasting hydrological growing seasons in 2006 [wet with total precipitation 11.2% above the long-term mean (348 mm)] and 2007 (dry with total precipitation 46.7% below the long-term mean). The responses of ecosystem carbon fluxes to warming and nitrogen addition did not change between the two growing seasons; warming had no effects on net ecosystem C exchange (NEE) or its two components: gross ecosystem productivity (GEP) and ecosystem respiration (ER). In contrast, nitrogen addition stimulated GEP but did not affect ER, leading to positive responses of NEE. At the same site, Niu et al. (2010) conducted an experimental study to examine effects of nitrogen addition on NEE in terms of nitrogen alone or combination with phosphorous (P) in both clipped and unclipped plots from 2005 to 2008. Their results showed that over the 4 studied years, nitrogen addition significantly stimulated growing-season NEE, on average, by 27%, and that neither the main effects of added phosphorus or clipping nor their interactions with added nitrogen were statistically significant on NEE in any of the 4 studied years. Although added nitrogen considerably increased NEE by 60% in 2005 and 21% in 2006, its effect was not significant in 2007 and 2008. They further pointed out that the magnitude of N stimulation on NEE decreased with time.

A field experiment in Duolun County between April 2005 and October 2006 was conducted to examine effects of topography, fire, nitrogen fertilization, and their potential interactions on soil respiration (Xu and Wan, 2008). Results indicated that mean soil respiration was 6.0% higher in the lower than upper slope over the two growing seasons, and that annual burning in early spring caused constant increases in soil respiration (23.8%) over the two growing seasons. Xu and Wan (2008) reported that the influences of fire on soil respiration varied with both season and topographic position, and that soil respiration in the fertilized plots was 11.4% greater than that in the unfertilized plots.

To understand how nitrogen deposition and elevated atmospheric CO_2 concentration affect forest floor soil respiration in subtropical China, Deng et al. (2010) grew tree seedlings in 10 large open-top chambers. Soil respiration displayed strong seasonal patterns with higher values in the wet season (April–September) and lower values in the dry season (October–March) in all treatments. Both CO_2 and N treatments significantly affected soil respiration, and there was a significant interaction between elevated CO_2 and N addition. The stimulatory effect of individual elevated CO_2 (an $\sim$29% increase) was maintained throughout the experimental period. The positive effect of N addition was found only in 2006 (an 8.17% increase), and then was weakened over time. Their combined effect on soil respiration (an $\sim$50% increase) was greater than the impact of either one alone.

Based on the data of the second national soil survey in China, Xu et al. (2006a) studied the coupling characteristics and spatial variation of SOC and total nitrogen (TN) in the plow layers of paddy and upland fields. Their results showed that SOC content and TN content were higher in paddy fields than in upland fields by 47.8% and 45.5%, respectively, but spatial variations of SOC and TN contents were higher in upland than in paddy fields. The ratio (C/N) of SOC to TN was $\sim$10.8 in paddy fields and $>$9.9 in upland fields. A significant regional variation of C/N ratio was recorded in upland fields. SOC was positively correlated with TN, with correlation coefficients all $>$0.8 in paddy and upland fields except in North China. Therefore, there existed a coupled relationship between SOC and TN (Xu et al., 2006a).

4.2 *Impacts of climate change*

Using a total of 886 datasets distributed in different regions of China, which were obtained from the second National Soil Survey of China that was completed in the early 1980s, Dai and Huang (2006) investigated the relation of soil organic matter (SOM) concentration to climate and altitude. The results showed that surface SOM concentration was generally negatively correlated with annual mean temperature (T) and positively correlated with annual mean precipitation (P) and altitude (H). Multiple regression models with different combination of T, P, and H could explain 41.5%-56.2% of the variability in surface SOM concentration for different geographical regions, whereas the driving variables were different (Dai and Huang, 2006).

Niu et al. (2008) conducted a field experiment manipulating temperature and precipitation in a temperate steppe in North China since 2005. The results for the first 2 years showed that gross ecosystem productivity (GEP) was higher than ecosystem respiration, leading to net carbon sink (measured by NEE) over the growing season at the study site. The interannual variation of NEE resulted from the difference in annual mean precipitation. Experimental warming reduced GEP and NEE, whereas increased precipitation stimulated ecosystem carbon and water fluxes in both years. Increased precipitation also alleviated the negative effect of experimental warming on NEE. They pointed out that water availability played a dominant role in regulating ecosystem carbon and water fluxes and their responses to climatic change in the temperate steppe of North China.

Based on climate change projections of 21st century under the Special Report on Emissions Scenarios (SRES) A2A, B2A and A1B (IPCC, 2000), Guo et al. (2010) studied the responses of yields and water use efficiencies of wheat and maize to climate change scenarios over the North China Plain. The projected climate results were used to drive CERES-W (wheat) and -M (maize) models. Their simulated results showed that under the same scenario, the wheat yield would increase due to climatic warming, whereas the maize yield would decrease. The simulated results further indicate that under B2A in the 2090s, average wheat yield and maize yield would respectively increase 9.8% and 3.2% without CO_2 fertilization in this region, and that if atmospheric CO_2 concentration reached nearly 600 ppm, wheat and maize yields would increase 38% and 12% and water use efficiencies would improve 40% and 25%, respectively, compared to those without CO_2 fertilization. In that study, the nitrogen effect was not included.

Using the process-based forest growth and carbon and nitrogen model of TRIPLEX, Peng et al. (2009) investigated the potential impacts of climate change and increasing atmospheric CO_2 on forest NPP and carbon budgets in Northeast China. The combined effects of climate change and CO_2 fertilization on the increase of NPP were estimated to be 10%–12% for the 2030s and 28%–37% for the 2090s. The simulated effects of CO_2 fertilization significantly offset the soil carbon loss due to climate change alone (Peng et al., 2009). Large uncertainties occur in the estimate of climate change impacts, due to many physical, biological, and social-economic processes. Tao et al. (2009b) developed a new super-ensemble based probabilistic projection approach to account for the uncertainties from CO_2 emission scenarios, climate change scenarios, and biophysical processes in the impact assessment model; it was used for maize production in the North China Plain in the future. The new process-based general crop model called MCWLA (Tao et al., 2009a) was used in their work. Using this model, the expected yield changes were −9.7%, −15.7%, −24.7% across the maize cultivation grids in Henan province during the 2020s, 2050s, and 2080s, relative to 1961–1990, respectively.

The relationship between NPP and climate change on interannual and decadal scales was explored by Mao et al. (2010) in Chinese terrestrial ecosystem with the Modified Sheffield Dynamic Global Vegetation Model (M-SDGVM) during 1981–2000. The results from M-SDGVM were in agreement with the NPP data from 743 sites. Compared to the 1980s, NPP in the 1990s increased in most of China with a high degree of spatial heterogeneity. The interannual variation of the total NPP showed a more significant correlation with temperature (i.e., relativity and probability were R= 0.61, P= 0.00403) than with precipitation ($R = 0.40$, $P = 0.08352$). Mao et al. (2010) also pointed out that CO_2 fertilization might play a key role in the increase of terrestrial ecosystem NPP over continental China, and that CO_2 stimulation increased with CO_2concentrations, and also with the climate variability of the 1980s and 1990s.

4.3 *Atmosphere–land–ocean coupled model*

In the Earth system, the atmosphere, land, and ocean are coupled through the exchanges of momentum, energy, and mass at their interfaces. For the carbon and nitrogen cycles, and for their interactions with climate change, study using coupled systems is very important. Over last several years, different coupled systems have been established.

A two-way coupled model, the Atmosphere–Vegetation Interaction Model-Global Ocean–Atmosphere–Land System model (AVIM-GOALS) was employed to simulate the surface physical fluxes and NPP (Dan and Ji, 2007). Their results showed that the annual NPP agreed well with the IGBP NPP data except for the lower value in northern high latitudes. All physical and biological fields in northern mid-latitudes had the largest seasonality, and the seasonality of these fields was highly correlated with each other. Using this data and the AVIM-GOALS model, Dan et al. (2007) analyzed the relationship between NPP and climate change. The globally averaged NPP of 447.47 g C m^{-2} yr^{-1} was close to the IGBP data of 450.42 g C m^{-2} yr^{-1}. The globally relative error of simulated NPP against IGBP data was ∼20% and was also comparable to other global biogeochemical models. Meridional variations of globally zonal mean NPP corresponded more to the meridional change of precipitation than to that of temperature. The global NPP for all vegetation types was highly correlated with precipitation.

Other than the work by Dan et al. (2007), Zhi et al. (2009a) employed the OGCM in the coupled GOALS-AVIM to study the main characteristics of interannual variations and the correlation between the atmospheric circulation and terrestrial ecosystem. The interannual variation revealed some distinct characteristics of the geographical distribution. Both NPP and LAI exhibited quasi 1-2-year cycles, whereas precipitation and surface temperatures exhibited 2–4-year cycles. Using singular value decomposition (SVD) analysis, results showed that the strengthening and weakening of the East Asian monsoon, characterized by the geopotential heights at 500 hPa and the wind fields at 850 hPa, corresponded to the spatio-temporal NPP pattern. In addition, the correlations between NPP and the air temperature, precipitation, and solar radiation were different in interannual variability because of the variation in vegetation types. Using the results from the same GOALS-AVIM, Zhi et al. (2009b) analyzed the Indian Ocean SST abnormality and its relations with NPP at the land surface in South Asia. Their correlation analysis showed that the consistent warming or cooling in the equatorial Indian Ocean had a positive lag correlation with the Niño3 index of the equatorial Pacific Ocean. The increase or decrease of summer monsoon in the Indian Ocean and South Asia caused the precipitation abnormity in South Asia, leading to the increase or decrease of NPP abnormity in this region.

Using the modified AVIM (AVIM2), in which a soil carbon module was included, Ji et al. (2008) investigated the change in carbon exchange between Chinese terrestrial ecosystem and the atmosphere, and the carbon storage in vegetation and soil during the 21st century. Future climate data were obtained from the regional climate model of the Hadley Centre under SRES B2 scenario. Under the B2 scenario and changing atmospheric CO_2 concentration, NPP for China will increase continuously from 2.94 Pg C yr^{-1} at the end of the 20th century to 3.99 Pg C yr^{-1} by the end of the 21st century, and vegetation and soil carbon storage will increase to 110.3 Pg C. Meanwhile, NEP in China will continue to rise during the first and middle periods of the 21st century, and NEP will reach its peak around the 2050s, then it will decrease gradually and approach to zero by the end of the 21st century (Ji et al., 2008). Using the same AVIM2, Wu et al. (2010) further studied the impact of future climate change on terrestrial ecosystems over China at four warmer levels of 1°C, 2°C, 3°C, and 4°C. As projected temperature increases, average NPP likely decreases in China as a whole. The Tibetan Plateau is the only ecoregion with increasing NPP as the climate becomes warmer. Wu et al. (2010) pointed out that in general, the influence of climate change on the terrestrial ecosystem NPP in China would increase with the increase in temperature, and that the northwest arid region would be expected to be the most vulnerable ecoregion. However, the interaction between NPP and climate change has not been considered in their studies because AVIM2 is not coupled directly to the atmospheric GCM. Hence, further investigation is required.

5. Concluding remarks

Advances in the study of the carbon and nitrogen cycles in China have been summarized, mainly including the carbon and nitrogen cycles in the terrestrial ecosystem and the ocean, and their relations to climate change. Many studies have shown that the Chinese terrestrial ecosystem was a net carbon sink in the 1980s–1990s, with an estimate of 0.19–0.26 Pg C yr^{-1} (Piao et al., 2009). An analysis of datasets from the literature showed the soil carbon sink of ~71 Tg C yr^{-1} from the early 1980s to the early 2000s (Huang et al., 2010b). Large uncertainty is mainly from the datasets and methods, land-use change, grassland management, and climate change. It has been estimated that both the natural wetland and the rice paddy emitted 1.76 Tg and 6.62 Tg of CH_4 per year for the period 1995–2004 and 2005–2009, respectively.

In addition, it has been estimated that land soil contained ~8.3 Pg N during the 1990s. Both fertilizer nitrogen input and animal population have greatly increased from 1961 to present. Lifestyle and agriculture practices have also changed. These substantially impact the balance of material cycles including carbon and nitrogen. Generally the excess N was partly maintained in farmland and was partly transported to water bodies. Atmospheric N deposition ranged from 18.4 kg hm^{-2} to 38.5 kg hm^{-2} in the North China Plain. It was estimated that China emitted ~1.1 TgN of N_2O, 9.4–10.4 TgN of NH_3, and 3.4 Tg NO_2-N to the atmosphere each year in 2000 or 2004.

It has been reported that the continental shelves are a sink for atmospheric CO_2 at middle to high latitudes (−0.33 Pg C yr^{-1}) but comprise a CO_2 source at low latitudes (0.11 Pg C yr^{-1}). The Yangtze River Estuary sediment may absorb at least ~4.1 Tg of atmospheric CO_2 every year. However, the main stream of the Yangtze Estuary generally emitted CO_2. The outer Yangtze Estuary served as a moderate or significant sink of atmospheric CO_2, except in autumn. The carbon fixed by phytoplankton was $\sim 2.22\times 10^{11}$ kg yr^{-1} with a clear seasonal variation in the Bohai Sea, the Yellow Sea, and the East China Sea. The carbon fixed by phytoplankton was $\sim 4.16\times 10^{11}$ kg yr^{-1} in the South China Sea. The surface pCO_2 values gradually increased from the continental shelf waters, the Bering Sea shelf slope, to the Bering Abyssal Plain (BAP) and the Canadian Basin.

Over the last 4 years, there have been some modeling studies about the ocean carbon cycle and some related work from Chinese scientists. An OGCM was generally employed to investigate the ocean carbon cycle. Using both North Pacific and global ocean models that were validated by several different passive tracers, the oceanic uptake of anthropogenic CO_2 was estimated. The global oceanic anthropogenic CO_2 uptake rates were 1.64 and 1.73 Pg C yr^{-1} for the two cases in the 1990s.

Riverine nitrogen input and atmospheric nitrogen deposition probably affect the nitrogen and carbon cycles in the ocean. In addition to atmospheric inorganic nitrogen deposition, atmospheric nitrogen deposition to the world's ocean may be important because in remote marine rains organic nitrogen was 62.8% ±3.3% of total nitrogen. The distribution of N_2O in surface seawater has also been discussed along the cruise tracks southward from 30°S to 67°S latitude in the Indian Ocean section.

The stimulatory effects of both individual elevated CO_2 and N addition on primary productivity were observed during the experimental period. However, their combined effects on soil respiration were also observed. Their combined effects on NEE in the terrestrial ecosystem need to be studied further. The ratio of soil organic carbon to total nitrogen (C/N) was ~10.8 in paddy fields, and it was >9.9 in upland fields. However, the regional variation of C/N ratio was very large in upland fields.

A two-way coupled model of AVIM-GOALS was used to simulate the surface physical fluxes and NPP in the terrestrial ecosystem in both inclusion and exclusion of OGCM. Using the same model with OGCM instead of SST forcing, the simulated results of the interannual variations of the spatial and temporal distributions of the surface air temperatures and precipitation were generally improved. Using the modified AVIM (AVIM2) with a soil carbon module, under the forcing of future climate change, NEP for China will increase continuously to the middle periods of the 21st century, and then will decrease gradually.

Although there are several estimates of carbon budget in the terrestrial ecosystems of China, a large degree of uncertainty remains. Nevertheless, there have no been any reports about the nitrogen budget on the national scale over the past 4 years. To reduce the uncertainty and to understand the relationship between climate change and carbon–nitrogen cycle, the following studies should be strengthened in the future. More observed data are definitely required. As pointed out by Fang et al. (2007), the uncertainty of estimate of carbon balance in the forest is mainly from inventory data. In addition to normal forest, other types of forest, including bamboo forest, farmland protection forest, and four-site greening trees, should be taken into account (Fang et al., 2007). The research on shrubland is still quite limited, but it is widely distributed and restores rapidly in China. For soil carbon sinks, land-use changes and their impacts on SOC need to be studied. This includes various conversions among wood land, grassland, and cropland. Grassland management and evaluation of changes in SOC in deep soil layers are another important focus (Huang et al., 2010b) that requires further study.

With the increase of population and alternation of food structure, agriculture practices in some East Asian countries have been changed. Persistently increased use of nitrogen fertilizer and increasing numbers of animals have resulted in accumulation of nitrogen in the environment, which generates the increase in atmospheric nitrogen deposition and nitrogen concentrations in the farmland, estuary, and ocean. The research on nitrogen cycle, including nitrogen budget on regional and national scale, is very limited. As N_2O continuously increases, its contribution to total radiative forcing will be enhanced. The carbon and nitrogen coupled effects are still poorly understood. This further affects ecological processes in the terrestrial and marine ecosystems. Studies of changes in some important nitrogen species such as NH_4^+, N_2O, and NO_3^-, in the atmosphere, soil, and ocean are important. Both CO_2 fertilization and N addition are required for further study, particularly study of long-term effects. Except for some observations of carbon and nitrogen in the estuary and river system as well as marginal seas of China, observations in the open ocean are very scarce in China, and they should be strengthened. Use of satellite data and improvement of data retrieval methods are important for modeling applications.

Persistent development and improvement of various models are considerably important, including inversion models and dynamic models, in which process-based models are generally fundamental. In the researches on the temporal evolution of carbon and nitrogen budgets, and on quantification of the spatiotemporal changes on regional and global scales, models are becoming increasingly significant. In recent years, although different carbon and nitrogen models in the terrestrial ecosystems and in the ocean have been developed in China, these models need to be further improved. To find out the factors influencing carbon and nitrogen cycles, considerable sensitivity tests should be conducted. In addition, the validation and uncertainties of models should be carefully examined.

Based on the observed data, inversion models are particularly useful for estimating the budget and spatio-temporal distributions of some important species in the both the atmosphere and the ocean in terms of circulation fields. In addition, data assimilation techniques should be used in the research of carbon and nitrogen cycles. To understand the interaction of carbon and nitrogen cycling with climate change, coupled models that include the physical climate model and the carbon (and/or nitrogen) cycle model should be continuously developed. This type of the coupled model is being developed into the earth system model.

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