

Construction and progress of Chinese terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation

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Abstract: Eddy Covariance technique (EC) achieves the direct measurement on ecosystem carbon, nitrogen and water fluxes, and it provides scientific data for accurately assessing ecosystem functions in mitigating global climate change. This paper briefly reviewed the construction and development of Chinese terrestrial ecosystem flux observation and research network (ChinaFLUX), and systematically introduced the design principle and technology of the terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation system of ChinaFLUX. In addition, this paper summarized the main progress of ChinaFLUX in the ecosystem carbon, nitrogen and water exchange and environmental controlling mechanisms, the spatial pattern of carbon, nitrogen and water fluxes and biogeographical mechanisms, and the regional terrestrial ecosystem carbon budget assessment. Finally, the prospects and emphases of the terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation of ChinaFLUX are put forward to provide theoretical references for the development of flux observation and research in China.

Keywords: eddy covariance technique; carbon-water-nitrogen fluxes; coupling cycle; coordinated observation; ChinaFLUX

1 Introduction

Accurately assessing the global, regional and national terrestrial ecosystem carbon budget and carbon exchange is an important theme in the global climate change researches. The assessment underlies the scientific basis to support the international joint actions to mitigate and adapt to climate change in the “United Nations Framework Convention on Climate Change (UNFCCC)” (Le Quéré *et al.*, 2013). In recent decades, China's economy experi-

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ences rapid development. The amount and growth rate of greenhouse gas emissions of China already leaped to the first in the world (Liu *et al.*, 2015). Therefore, China faces enormous challenges in reducing the greenhouse gas emission and effectively governing the atmospheric pollution.

Greenhouse gases in the atmosphere mainly consist of CO₂, H₂O, CH₄, NO, NO₂, N₂O, NH₃, HNO₃ and other trace gases. The greenhouse gas exchange between the ecosystem and the atmosphere are all closely related to the ecosystem carbon, nitrogen and water cycles. Coordinated observation on carbon, nitrogen and water fluxes between ecosystem and the atmosphere is an important approach to evaluate the terrestrial ecosystem functions of greenhouse gas absorption and digestion (Yu *et al.*, 2014a). Also, terrestrial ecosystem carbon, nitrogen and water cycle processes and their coupling relations are the core processes in the global-scale biogeochemical cycles to determine the ecosystem services. Therefore, studies on terrestrial ecosystem carbon, nitrogen and water cycle processes and their coupling relations are the scientific foundation for understanding the interactions between ecosystem and global climate change, and are the frontiers in current geographical and ecological researches (Yu *et al.*, 2013a, 2014b).

The development and application of flux observation technology, represented by the greenhouse gas (CO₂, H₂O and CH₄) eddy covariance techniques, could provide us the long-term continuous, high-frequency, multiple elements synchronous, and across sites networked ecosystem carbon, nitrogen and water fluxes and environmental elements data (Baldocchi, 2008, 2014; Yu *et al.*, 2013a, 2014b). In the past two decades, the ecosystem CO₂ and H₂O flux observation have been carried out worldwide, and accumulated large amount of scientific data (Luyseart *et al.*, 2007; Reichstein *et al.*, 2014; Baldocchi *et al.*, 2008, 2014; Yu *et al.*, 2013b). Recently, continuous observation of CH₄, NO, NO₂, N₂O, NH₃, HNO₃ and other carbon, nitrogen and water trace gas fluxes is gradually applied in the field (Baldocchi, 2014). These data lay the solid foundation for assessing the carbon, nitrogen and water and trace gas budget, exploring the controlling mechanism for carbon, nitrogen and water fluxes and their coupling relations, and predicting the responses and adaption of carbon, nitrogen and water cycle processes to global climate change (Yu *et al.*, 2014b).

The Chinese terrestrial ecosystem flux observation and research network (ChinaFLUX) was established in 2001. Continuous measurement of CO₂, H₂O and energy fluxes, synchronous environmental elements, and ecosystem properties were started since 2002 (Yu *et al.*, 2006a, b; Yu and Sun, 2006). ChinaFLUX has made great progress in the original data accumulation, mechanism of ecosystem carbon, water cycle process, the model system development, and the regional carbon, water budget quantitative evaluation (Yu *et al.*, 2014a). It promotes the development of flux researches in China and bridges the gaps in global flux observation thus gains worldwide appreciation (Leuning and Yu, 2006; Doherty *et al.*, 2009; Saigusa *et al.*, 2013; Stoy *et al.*, 2013). Recently, ChinaFLUX takes the lead to develop the terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation system, promote the observation and field control experiment network researches on ecosystem carbon, nitrogen and water coupling cycles and their responses to climate change, and expand the frontier research field in the terrestrial ecosystem and global change science (Yu *et al.*, 2013a; Yu *et al.*, 2014a, 2014b).

Based on the previous introduction of ChinaFLUX and its theoretic framework of terres-

trial ecosystem carbon, nitrogen and water coupling cycle researches (Yu *et al.*, 2006b, 2013a, 2014a, 2014b), this study briefly reviewed the construction and development history of ChinaFLUX, and mainly systematically summarized the main progress of ChinaFLUX in the key technology exploration and application of the carbon, nitrogen and water fluxes coordinated observation system, and progress in the studies on the ecosystem carbon, nitrogen and water exchange and environmental controlling mechanisms, the spatial pattern of carbon, nitrogen and water fluxes and biogeographical mechanisms, and regional terrestrial ecosystem carbon budget assessment. Finally, the future development strategies of ChinaFLUX coordinated observation system on terrestrial ecosystem carbon, nitrogen and water fluxes are proposed so as to provide theoretical references for the development of flux observation and research in China.

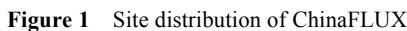
2 Construction of the ChinaFLUX coordinated observation on terrestrial ecosystem carbon, nitrogen and water fluxes

2.1 Establishment and development of ChinaFLUX

Supported by the Knowledge Innovation Program of the Chinese Academy of Sciences “Study on Carbon Budget in Terrestrial and Marginal Sea Ecosystems of China”, the Chinese Terrestrial Ecosystem Flux Observation and Research Network (ChinaFLUX) was launched in 2001. By one year’s well-design on the observation system, instrument selection and site investigation, the first 8 stations (4 forests, 3 grasslands and 1 cropland) and 1 integrated research center of ChinaFLUX were established in 2002. Since then, the long-term coordinated flux measurement is started formally in China (Yu *et al.*, 2006a, 2006b; Yu and Sun, 2006).

ChinaFLUX was subsequently supported by a series of programs. Such projects promote the development of ChinaFLUX through the increase of flux sites, extension of spatial representativeness and improvement of observation capability. ChinaFLUX gradually become a unique scientific and technological platform for carbon cycle and global change in China (Yu *et al.*, 2014a). ChinaFLUX also promotes its international development, with great achievement in prompting the recombination of Asian flux network (AsiaFlux). Currently, ChinaFLUX becomes not only a distinctive observation and research network in Chinese Ecosystem Research Network (CERN), but also an important component of the Asian and global flux network (FLUXNET).

The development of ChinaFLUX takes the lead in the construction of flux stations from forestry, agricultural, meteorological departments and some universities, and also provides the important basis for coordinated flux measurement and resources integration among different departments in China. In 2014, the Chinese Flux Observation and Research League (new ChinaFLUX) was formed through the combination between ChinaFLUX and other flux stations from different departments. Currently, there are 71 flux stations in ChinaFLUX, which includes 22 forests, 17 grasslands (deserts), 17 croplands, 13 wetlands, 1 urban and 1 lake sub-network. The sites cover tropical, temperate and boreal typical climate zones in China (Figure 1). The national scale ecosystem flux observation and research network has been preliminarily established.



The scientific targets of ChinaFLUX is designed to (1) establish the national ecosystem observation and research platform; (2) accumulate the long-term scientific data of carbon, nitrogen and water fluxes, meteorological, biotic and soil factors, and ecosystem elements; (3) organize the mechanism researches on carbon, nitrogen and water coupling cycle processes and environmental regulation across ecosystem, transect, regional and global scales; (4) provide scientific support for dealing with climate change and promoting the sustainable development of environment and society (Figure 2) (Yu *et al.*, 2014a).

The observational technology development largely prompts the capability of ChinaFLUX in the typical terrestrial ecosystem carbon, nitrogen and water flux coordinated observation, national scale carbon and nitrogen flux network observation, and adaptation of ecosystem carbon, nitrogen and water cycle to global change field control experimental researches. ChinaFLUX proposed the development strategy to construct the coordinated observation on terrestrial ecosystem carbon, nitrogen and water fluxes in China.

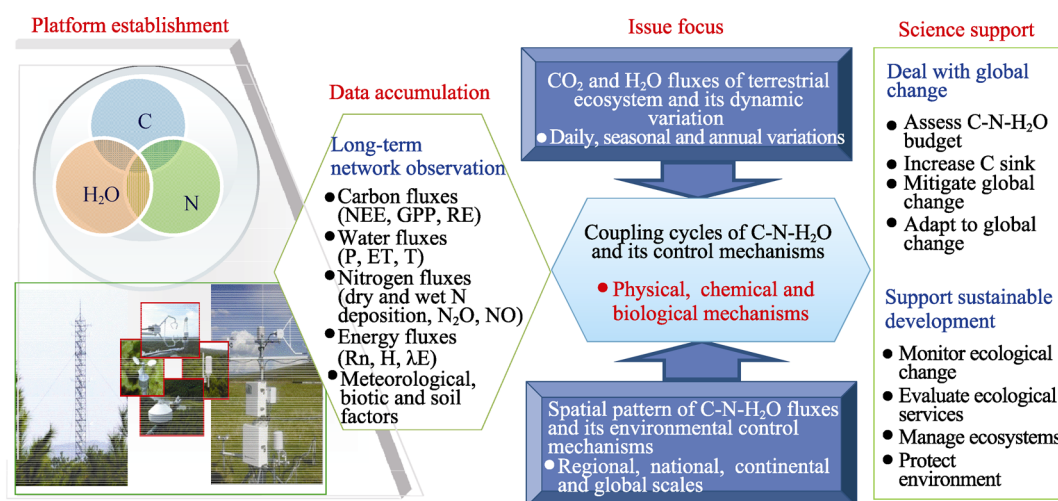


Figure 2 Scientific targets of ChinaFLUX

2.3 Main scientific issues in the coordinated observation on ecosystem carbon, nitrogen and water fluxes of ChinaFLUX

Research on the ecosystem carbon, nitrogen and water cycles and their coupling relationships is the scientific requirement for regulating and managing ecosystem processes to mitigate global change. The key mission of ecosystem carbon, nitrogen, and water fluxes researches of ChinaFLUX is to cognize the ecosystem carbon, nitrogen and water cycle processes and its environmental controlling mechanism, multi-scale temporal variation of carbon, nitrogen, water fluxes and its dynamic mechanism, and ecosystem carbon, nitrogen, water coupling cycles response to global change and its adaptive mechanisms. Specifically, ChinaFLUX mainly focuses on four scientific issues (Figure 3): (1) the key processes and its biological controls of the ecosystem carbon, nitrogen and water coupling cycles; (2) the stoichiometric equilibrium and its environmental responses of ecosystem carbon, nitrogen and water fluxes; (3) the regulation mechanism of the ecosystem carbon, nitrogen and water coupling cycles on the spatio-temporal pattern of terrestrial ecosystem carbon sink/source; (4) the response and adaptation of the biological processes of ecosystem carbon, nitrogen and water coupling cycles to global change (Yu *et al.*, 2014b).

3 Construction and key technology of the coordinated observation on ecosystem carbon, nitrogen and water fluxes of ChinaFLUX

3.1 Design of carbon, nitrogen and water multi-elements coordinated observation system in typical ecosystems

The systematic design of ChinaFLUX persists in combining long-term continuous instrumental observations and control experiments as guideline. It emphasizes the synthetic observation of multiple greenhouse gas fluxes, environmental elements and ecological processes, as well as the coordinated observation of carbon-nitrogen-water fluxes and cycle processes. ChinaFLUX focuses on the development of the continuous and in situ carbon and

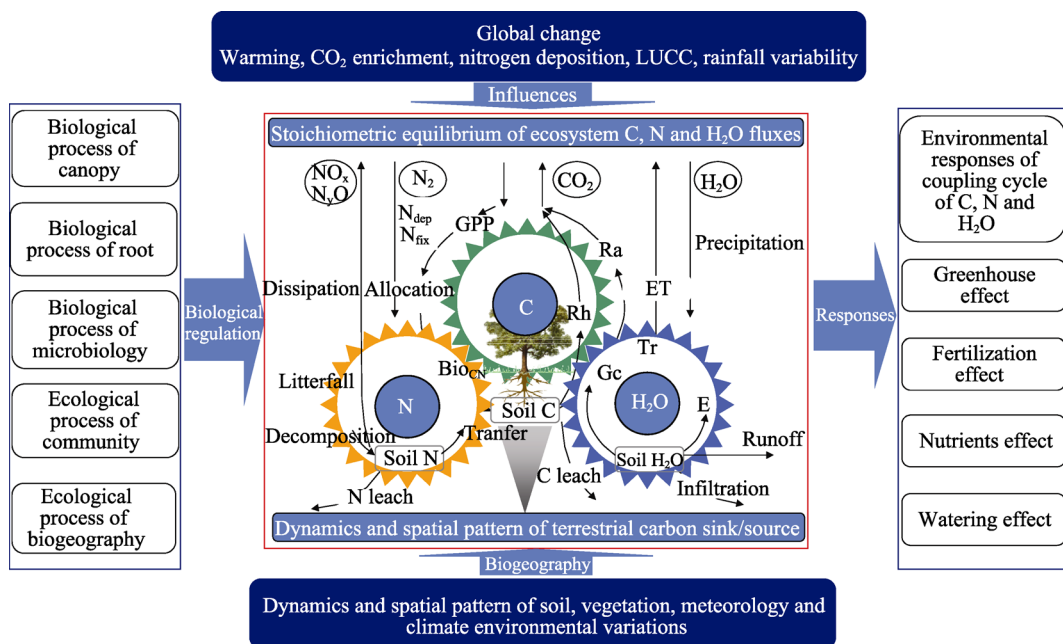


Figure 3 Scientific issues of the coordinated observation on ecosystem carbon, nitrogen and water fluxes of ChinaFLUX

C: Carbon; N: Nitrogen; GPP: Gross primary production; Ra: Autotrophic respiration; Rh: Heterotrophic respiration; ET: Ecosystem evapotranspiration; Tr: Transpiration; E: Evaporation; LUCC: Land use cover change

water stable isotope fluxes observational techniques, soil CO₂, CH₄ and N₂O fluxes coordinated observational technique, and the atmospheric deposition flux observation and N tracer technique. By systematically integration of ecological, meteorological and isotopic techniques, ChinaFLUX prospectively built the carbon, nitrogen and water multi-elements coordinated observation system in typical ecosystems (Figure 4) (Yu *et al.*, 2014a).

The development of in situ ecosystem carbon and water stable isotope fluxes measurement technique overcame the problem of nonlinear response of instruments (Wen *et al.*, 2008, 2012). It allowed in situ and continuous measurement of $\delta^{18}\text{O}$ and δD of atmospheric water vapor (Wen *et al.*, 2010; Zhang *et al.*, 2011; Huang *et al.*, 2014), and isotopic ratio and flux ratio of atmospheric CO₂ $\delta^{13}\text{C}$ (Pang *et al.*, 2016). This technology broke through the bottleneck of coordinated observation of eddy covariance and stable isotopes. It achieves the coordinated observation of ecosystem carbon and water vapor flux and $\delta^{18}\text{O}$, δD and $\delta^{13}\text{C}$ fluxes (Wen *et al.*, 2012, 2015).

Based on the theory of close path non-steady state measurement, the “automatic multi-channels soil CO₂, CH₄ and N₂O flux coordinated observation device” was developed. This device adopted parallel connection to optimize the pressure fluctuation and reduce the system leakage based on a composite technology of near infrared and mid-infrared laser. Meanwhile, the pressure balance and gas mixing efficiency were improved. It could measure CO₂, CH₄ and N₂O fluxes simultaneously, and collect data in the field automatically. The device increased the spatio-temporal representativeness of observational data and is useful for the synthesis of synchronous CO₂, CH₄ and N₂O fluxes.

Atmospheric nitrogen deposition observation and nitrogen stable isotope tracing technol-

ogy are useful technologies for ecosystem nitrogen cycle researches. In the coordinated observation system of ChinaFLUX, the technical specifications for atmospheric wet nitrogen deposition observation were compiled (Sheng *et al.*, 2010; Zhan *et al.*, 2014; Zhu *et al.*, 2015). These specifications provided a series of uniform operate procedures, including monitoring equipment setup, samples collection and data analysis. Now, these specifications have been used by many scientists in specific sites or regions (Sheng *et al.*, 2010; Zhan *et al.*, 2014; Zhu *et al.*, 2015). It improves the normalization of atmospheric wet nitrogen deposition in China to a large extent (Jia *et al.*, 2014; Zhu *et al.*, 2015). The application of stable nitrogen isotopic tracer technology including the natural abundance of ^{15}N and addition of ^{15}N maker in the nitrogen cycle researches were also discussed (Sheng *et al.*, 2012, 2014; Xu *et al.*, 2014; Zhan *et al.*, 2014, 2015; Zhu *et al.*, 2015). Additionally, to improve the method of static chambers and gas chromatography for soil N_2O emission measurement, scientists of ChinaFLUX conducted systematic comparative experiments in aspects of static chambers construction, sampling plots setup, sampling frequency, and instruments (Zheng *et al.*, 2008). Nowadays, the findings have formed a series of operational procedure and been widely used by many scientists (Zheng *et al.*, 2008; Fang *et al.*, 2014a, 2014b; Wang *et al.*, 2015).

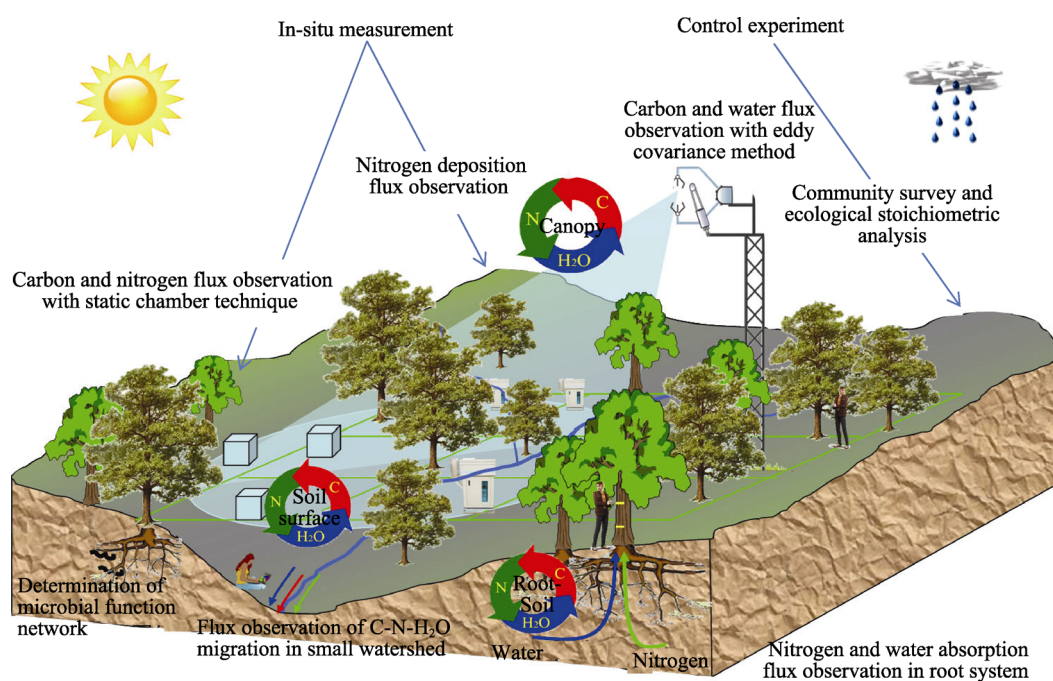


Figure 4 The carbon, nitrogen and water multi-elements coordinated observation system in typical ecosystems

3.2 Design of multi-scale carbon, nitrogen and water coordinated observation system

ChinaFLUX consistently emphasizes optimizing the spatial distribution of experiment sites. It follows the scientific principles of the geographic heterogeneity of ecosystem patterns, the diversity of ecosystem types at regional scale, and the representativeness in critical zones. By adopting the integrated and optimized approaches of the site-transect-region remote sensing observation, ChinaFLUX systematically designs the multi-scale carbon, nitrogen,

water fluxes coordinated observation system. Along the transect, ChinaFLUX integrate science and technology resources of flux measurements, control experiments and transect researches to promote the build up and development of flux observation and experimental research network platform which underlies the foundation of super flux observational sites.

3.3 The development of ecosystem carbon, nitrogen and water models and model-data fusion system

Process-based ecosystem models and remote sensing models are important tools to estimate and predict dynamics variations and spatial patterns of ecosystem carbon, nitrogen, and water fluxes. ChinaFLUX community modified several process-based models and remote sensing models, such as CEVSA (Cao *et al.*, 2005; Gu *et al.*, 2010), In-TEC (Wang *et al.*, 2007), EALCO (Mi *et al.*, 2007; Mi *et al.*, 2009), and BEPS (Wang *et al.*, 2005; Ju *et al.*, 2010), and VPM (Li *et al.*, 2007; Wu *et al.*, 2008). Meanwhile, many new models have been developed including AVIM2 (Ji *et al.*, 2008; Huang *et al.*, 2014), CEVSA2 (Gu *et al.*, 2010; Gu *et al.*, 2015), the evapo-transpiration model (Hu *et al.*, 2013; Ren *et al.*, 2005), a MODIS-based Photosynthetic Capacity Model (Gao *et al.*, 2014), a remote sensing model for respiration ReRSM (Gao *et al.*, 2015), and the statistical model GSM (Zheng *et al.*, 2009; Yu *et al.*, 2010; Zhu *et al.*, 2014a).

In addition, a Model-Data Fusion System (MDFS) has been developed based on a series of algorithms including the Markov-Chain Monte Carlo method, the Monte Carlo Simulated Annealing method, and the sobol' method (Zhang *et al.*, 2009, 2010; Ren *et al.*, 2012) to quantify and minimize the model uncertainty. This system has been used for the uncertainty estimation for eddy flux measurements (He *et al.*, 2010; Liu *et al.*, 2009), model parameter estimation and carbon fluxes simulation and uncertainty estimation at site (Zhang *et al.*, 2010; Liu *et al.*, 2012, 2015) and regional scales (He *et al.*, 2014), which provides an effective solution for scaling from site to regional levels and a platform for assessing the carbon and water balances on the national scale.

4 Spatio-temporal patterns of terrestrial ecosystem carbon, nitrogen and water fluxes and environmental control mechanisms

By more than 10-year's network observation, ChinaFLUX accumulates the valuable and unique data of ecosystem carbon, nitrogen and water fluxes in China. ChinaFLUX conducted a series of studies and gained great progress in the aspects of ecosystem carbon, nitrogen and water exchange dynamics and environmental controlling mechanisms, the spatial pattern of carbon, nitrogen and water fluxes and biogeographical mechanisms, and the regional terrestrial ecosystem carbon budget assessment.

4.1 Evaluation of ecosystem carbon sink/source based on flux measurement

The carbon sink/source of ecosystem in typical climate zones were investigated (Table 1). Forests were found to have a strong carbon sequestration capacity. The highest carbon sink appeared in central subtropical forests ($550 \pm 258 \text{ g C m}^{-2} \text{ yr}^{-1}$), and followed by warm temperate forests ($492 \pm 37 \text{ g C m}^{-2} \text{ yr}^{-1}$) and northern subtropical forests ($343 \text{ g C m}^{-2} \text{ yr}^{-1}$).

Table 1 Statistics of carbon fluxes of ecosystems in typical climate zones of China (Mean \pm Standard deviation)

Ecosys-tem types	Climate zones	NEP (g C m ⁻² yr ⁻¹)	GPP (g C m ⁻² yr ⁻¹)	RE (g C m ⁻² yr ⁻¹)	Flux sites	References
Forest	Tropical	202±47	2156±263	1954±310	XSBN, JFL	Zhang <i>et al.</i> , 2010; Chen <i>et al.</i> , 2010
	Southern sub-tropical	250±206	1424±81	1174±287	DHS, DG	Sun <i>et al.</i> , 2012; Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014
	Central subtropical	550±258	1801±167	1253±226	HT, AQ, YY, QYZ, ALS	Yu <i>et al.</i> , 2013; Chen <i>et al.</i> , 2014; Tan <i>et al.</i> , 2011; Zhang <i>et al.</i> , 2010; Zhao <i>et al.</i> , 2011; Han <i>et al.</i> , 2008
	Northern sub-tropical	343	1288	965	XP	Geng <i>et al.</i> , 2011
	Warm temperate	492±37	1379±103	887±67	DX, XLD	Huang <i>et al.</i> , 2011; Zha <i>et al.</i> , 2007; Fang <i>et al.</i> , 2011
	Temperate	302	1338	1036	CBS	Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014
	Cool temperate	135±114	970±326	774±298	HZ, LS	Wang <i>et al.</i> , 2008; Cui <i>et al.</i> , 2007; Qiu <i>et al.</i> , 2011; Zhou <i>et al.</i> , 2010
Grass-land	Temperate	24±83	282±108	260±95	DL, NM, CL, XLHT (1, 2, 3), KBQ, TY, LP, FK	Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014; FLUXNET, 2013; Du <i>et al.</i> , 2012; Wang <i>et al.</i> , 2008; Liu <i>et al.</i> , 2011a, 2011b; Dong <i>et al.</i> , 2011a, 2011b; Zhang <i>et al.</i> , 2007
	Alpine	45±59	470±193	424±146	DX, SJY, HB	Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014; Wu <i>et al.</i> , 2010; Wang <i>et al.</i> , 2012
Cropland	Subtropical	675	1598	923	TY	Zhu <i>et al.</i> , 2005
	Warm temperate	462±136	1792±64	1329±72	WS, YC	Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014; Lei <i>et al.</i> , 2010a, 2010b
	Temperate semi-arid	75	381	306	DL	Zhang <i>et al.</i> , 2007; FLUXNET, 2013
Wetland	Subtropical	577±123	1553±155	977±133	DT(1,2,3)	Guo <i>et al.</i> , 2010; Yan <i>et al.</i> , 2009; FLUXNET 2103
	Warm temperate	65	1298	1233	PJ	Zhou <i>et al.</i> , 2009, 2010
	Cool temperate	98±148	570±116	473±107	SJ (1,2,3)	Song <i>et al.</i> , 2007
	alpine	-79	489	568	HBSD	Yu <i>et al.</i> , 2013b; Chen <i>et al.</i> , 2014

Cool temperate forests showed lower carbon sink compared to warm temperate and temperate forests. Studies of specific ecosystem suggest that mature forests in Northeast, Southeast, and Southwest (Zhang *et al.*, 2006a; Yu *et al.*, 2008, 2013; Liu *et al.*, 2014a; Tan *et al.*, 2010, 2012; Guan *et al.*, 2006; Zhang *et al.*, 2006b; Yan *et al.*, 2012) and subtropical plantations (Liu *et al.*, 2006; Wen *et al.*, 2010) had strong carbon sequestration capacity.

The carbon sink magnitude of grasslands was obviously lower than that of forests. Temperate steppes and alpine meadows served as weak carbon sink (24±83, 45±59 g C m⁻² yr⁻¹). The grasslands in northern China probably served as a weak carbon source after disturbances, which differed substantially among ecosystems and years (Shi *et al.*, 2006; Zhao *et al.*, 2006; Li *et al.*, 2006; Wang *et al.*, 2011; Fu *et al.*, 2006, 2009; Yu *et al.*, 2013b).

The magnitude of carbon sink differed substantially in croplands and wetlands. Croplands in temperate semi-arid zones (75 g C m⁻² yr⁻¹) showed a much lower carbon sink than crop-

lands in other climate zones ($675, 462 \pm 136 \text{ g C m}^{-2} \text{ yr}^{-1}$). The subtropical coastal wetland had a high net carbon uptake capacity.

4.2 Dynamics and environmental controlling on ecosystem CO₂ flux

4.2.1 Dynamics of ecosystem CO₂ flux across zonal vegetation

Based on the long-term and continuous flux measurement, the diurnal, seasonal and inter-annual variations across different zonal vegetations were analyzed. (1) At daily scale, ecosystem CO₂ flux was generally coherent with radiation and temperature which attained the peak at the middle of the day (Yu and Sun, 2006). (2) At seasonal scale, apparent unimodal variations of CO₂ flux were presented for both mid- and high latitude and alpine vegetation in northern China and the Tibetan Plateau, while the differences among seasons were reduced in subtropical and tropical vegetation. Due to the limitation of soil moisture and low temperature, ecosystem CO₂ flux of grassland in northern China and semi-arid region of the Tibetan Plateau presented high sensitivity to precipitation. For the cropland in northern China, bimodality pattern was appeared due to the crop rotation. (3) Due to the environmental changes, apparent interannual variability of CO₂ flux was appeared in different ecosystems (Yan *et al.*, 2013; Tan *et al.*, 2012; Wen *et al.*, 2010).

4.2.2 Environmental responses of ecosystem CO₂ flux

From the synthesized analysis on ecosystem CO₂ flux, the environmental responses of different terrestrial ecosystems in China were presented. For example, the effects of diffuse radiation (Fan *et al.*, 2011; Zhang *et al.*, 2009, 2010, 2011), water supply (Wen *et al.*, 2006; Fu *et al.*, 2006; Hao *et al.*, 2010a; Wen *et al.*, 2010; Wang *et al.*, 2011), pulse rainfall (Hao *et al.*, 2010b, 2011, 2013; Yan *et al.*, 2011), and temporal distribution of precipitation (Yu *et al.*, 2005; Yan *et al.*, 2012, 2013) on ecosystem CO₂ flux were elucidated. At the same time, a series of important ecological phenomena and their controlling mechanism were illustrated. For example, the ‘light depress’ at ecosystem scale in temperate and alpine grasslands (Fu *et al.*, 2006, 2009), the nonlinear response of ecosystem carbon flux to temperature variation (Yu and Sun, 2008), heterogeneous response of soil respiration to temperature (Tan *et al.*, 2013; Jia *et al.*, 2013; Song *et al.*, 2013), the spatio-temporal variation of ecosystem light use efficiency (Yuan *et al.*, 2010; Zhang *et al.*, 2006c; Wu *et al.*, 2008), and the ‘carbon pool’ in mountain area (Yao *et al.*, 2012). Such studies enhance the understanding of the biotic and abiotic controlling mechanism of ecosystem CO₂ flux across different temporal scales, and the response and adaptation of ecosystem flux to global change.

4.3 The spatial pattern of ecosystem carbon fluxes and the underlying biogeographical mechanisms

4.3.1 Global pattern of ecosystem carbon fluxes and biogeographical mechanisms

Terrestrial ecosystems play an important role in regulating the atmospheric CO₂ concentration and mitigating the global warming. However, the carbon exchange between terrestrial ecosystems and the atmosphere varies substantially at the spatial scale. To reduce the uncertainty of terrestrial ecosystems in the global carbon budget, it is necessary to understand the spatial variability of carbon flux and its controlling mechanism. ChinaFLUX researchers based on the ecosystem carbon flux data, quantitatively evaluated the spatial variability of

ecosystem carbon flux in China (Yu *et al.*, 2013b). GPP, RE and NEP showed obvious latitudinal pattern and mean annual temperature and precipitation and their interaction explained more than 60% of the spatial variation of GPP, RE and NEP in China (Yu *et al.*, 2013b). Analyses of Asian, Northern Hemispheric and global carbon flux data all showed that the spatial variation of GPP, RE and NEP were mainly influenced by the pattern of mean annual temperature and precipitation (Yu *et al.*, 2013b; Chen *et al.*, 2013; Chen *et al.*, 2015a). In the Northern Hemisphere, the pattern of mean annual temperature, precipitation and vegetation index NDVI jointly explained large parts of the spatial variation of GPP and RE respectively (Chen *et al.*, 2015a). Further analysis revealed that the pattern of mean annual temperature and precipitation, through shaping the pattern of vegetation properties, to influence the spatial pattern of carbon fluxes (Chen *et al.*, 2015a). Series of results provide evidence to the theory of climate pattern shaping the spatial pattern of ecosystem carbon fluxes at the regional and global scales. It reveals the underlying biogeographical mechanisms for the spatial pattern of carbon fluxes, and puts forward new approach to analyze and evaluate the regional and global ecosystem carbon budget from the aspect of the geographical distribution of climate factors (Yu *et al.*, 2013b; Chen *et al.*, 2013; Chen *et al.*, 2015a).

4.3.2 High carbon sinks and interrelations among carbon fluxes at spatial pattern

Global analysis of carbon fluxes indicated that East Asian monsoon subtropical forests between 20°N and 40°N have high strength of carbon uptake and it attributes to the combined effects of the young stand ages, high nitrogen deposition and sufficient and synchronous water and heat availability (Yu *et al.*, 2014c). Integrative analysis of global carbon fluxes data showed that GPP and RE co-varied at the spatial pattern from regional to global scale (Yu *et al.*, 2013b; Chen *et al.*, 2013; Chen *et al.*, 2015b). The spatial pattern of GPP determined 90% of the global spatial pattern of RE and its underlying physiological mechanism due to the fact that production GPP functions as the direct substrate provider for respiration RE (Chen *et al.*, 2015b).

4.4 Dynamics of water vapor fluxes and water use efficiency and their environmental controlling mechanisms

4.4.1 The spatio-temporal variations of ecosystem evapotranspiration and their influencing factors in China

Evapotranspiration (ET) is an important component of water cycle and energy balance in terrestrial ecosystems (Wang and Dickinson, 2012). Investigating the spatio-temporal variations of ET and their influencing factors is of great significance for water resource management and assessment (Zheng *et al.*, 2016). Eddy covariance technique can directly measure water vapor fluxes between atmosphere and biosphere (Yu *et al.*, 2006; Baldocchi, 2008), which plays an important role in exploring ET spatio-temporal variations and their affecting factors. Based on eddy covariance measured water vapor fluxes, ChinaFLUX investigated the diurnal variation (Li *et al.*, 2010; Zheng *et al.*, 2014), the seasonal dynamics (Tang *et al.*, 2014; Zhou *et al.*, 2010), and the interannual variation (Zhou *et al.*, 2010; Xu *et al.*, 2014) of ET in typical ecosystems. The results revealed the hysteresis responses of ET to air temperature and vapor pressure deficit in its diurnal variation (Zheng *et al.*, 2014). The role of soil water content (Li *et al.*, 2010; Tang *et al.*, 2014) and air condition (Li *et al.*, 2010; Zhou

et al., 2010) in the seasonal dynamics of ET and the relative contributions of ecological responses and climate variation in ET interannual variations (Zhou *et al.*, 2010; Xu *et al.*, 2014) were also clarified. In addition, based on measured ET, ChinaFLUX also revised the Shuttleworth-Wallace model and applied it in forests and grasslands (Hu *et al.*, 2009; Hu *et al.*, 2013; Zhu *et al.*, 2015). ET components were also separated with hydrogen and oxygen isotope from isotope online observations, which provides a critical tool to reveal the variations of ET components (Hu *et al.*, 2014).

Based on the mechanism analysis of ET dynamics in typical ecosystems, ChinaFLUX also explored network observations to reveal the statistics of ET in typical regions and revealed the spatial variation of ET, especially the relationships between ET and climate and vegetation spatial patterns. The results indicated that annual net radiation, annual precipitation and annual mean temperature shaped the spatial pattern of ET, which provides a basis for assessing the spatial distribution of ET (Zheng *et al.*, 2016). Network measured ET was also used to optimize the ET remote sensing model and to assess the spatial distribution of ET in China (Li *et al.*, 2014).

4.4.2 The spatio-temporal variations of ecosystem water use efficiency and their environmental and biological controlling mechanisms

Water use efficiency (WUE) is an important parameter reflecting the interaction between carbon and water cycles. Analyzing the spatio-temporal variations of WUE, which would benefit for rational utilization of regional water resources, would improve our understanding on carbon and water cycles in terrestrial ecosystems (Zhu *et al.*, 2015). Eddy covariance technique, which simultaneously measures carbon and water fluxes, laid an important data basis for analyzing the variations of WUE. Using eddy covariance measured GPP and ET, ChinaFLUX analyzed the dynamic of WUE in typical forests (Yu *et al.*, 2008), grasslands (Hu *et al.*, 2008) and cropland (Zhao *et al.*, 2007) and found the “coupling and decoupling” phenomena in the dynamics of carbon and water fluxes. Then the biological and environmental mechanisms underlying the WUE dynamics (Yu *et al.*, 2008, Hu *et al.*, 2008) and their difference among regions were clarified (Zhu *et al.*, 2014).

In addition, based on network eddy covariance measurements, the spatial variations of WUE among forests (Yu *et al.*, 2008), grasslands (Hu *et al.*, 2008), and ecosystems having different ecosystem types (Zhu *et al.*, 2015) were investigated, which were found to be differed among ecosystem types. Annual mean air temperature and annual precipitation were found to be the dominant factors influencing the spatial variation of WUE among forests (Yu *et al.*, 2008), but leaf area index (LAI) was found to determine the spatial variation of WUE among grasslands (Hu *et al.*, 2008). Further analysis firstly illustrated the close relationship between WUE and altitude among different ecosystem types and found the spatial variation of WUE can be comprehensively reflected by elevation and LAI (Zhu *et al.*, 2015). Then the spatial distribution of WUE was obtained to analyze the water cost of carbon sequestration and the reasonable regions in afforestation. The water cost of carbon sequestration threshold for afforestation was found to be near 400–500 mm rainfall, which made the region on the west of the threshold having huge water limit risk in afforestation (Gao *et al.*, 2014).

4.5 Spatio-temporal patterns of atmospheric inorganic N deposition

4.5.1 Spatio-temporal patterns of atmospheric wet N deposition in China and the influencing factors

China has been considered as one of three regions with the highest atmospheric nitrogen (N) deposition in the world. Therefore, understanding the spatio-temporal patterns and factors of atmospheric N deposition is useful to evaluate its ecological effects on terrestrial ecosystems. Based on CERN and some other ecological observation sites, researchers established a national observation network to monitor atmospheric N deposition.

The network revealed the composition of the wet N deposition in China and highlighted the importance of total particulate N (TPN) through precipitation event. It was estimated, on the basis of the measured data, that the atmospheric wet N deposition of total dissolved N (TDN), $\text{NH}_4^+\text{-N}$, and $\text{NO}_3^-\text{-N}$ were 13.69, 7.25, and 5.93 kg N ha⁻¹ yr⁻¹, respectively. The ratio of $\text{NH}_4^+/\text{NO}_3^-$ was 1.22 on average at national scale. Furthermore, the deposition of TPN was about 4.33 kg N ha⁻¹ yr⁻¹, accounting for 24% of TN through precipitation event; these findings confirmed the ideas that atmospheric wet N deposition was underestimated without including TPN (Sheng *et al.*, 2012; Zhan *et al.*, 2014; Zhu *et al.*, 2015). Meanwhile, through analyzing the published monitoring data during 1980–2000, researchers found that atmospheric dissolved inorganic N deposition (DIN, including $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$) increased by 25% from the 1990s to 2000s in China (Jia *et al.*, 2014). Atmospheric wet N deposition was the highest over southern China and exhibited a decreasing gradient from southern to western and northern China. Precipitation, N fertilizer use, and energy consumption were significantly correlated with atmospheric wet N deposition (Zhu *et al.*, 2015).

4.5.2 Spatio-temporal patterns of atmospheric dry N deposition in China and influencing factors

Dry N deposition is an important component of total atmospheric N deposition. However, how to assess accurately atmospheric dry N deposition at regional and global scales is a big challenge for scientists, and the results have high uncertainty. Based on the chemical transformations between airborne reactive N, researchers developed new methods which can evaluate the spatial patterns and trends of dry deposition fluxes in 2005–2014 in China and globally from ground N concentrations and the Ozone Monitoring Instrument (OMI) NO_2 columns. The results showed that the average of dry N deposition fluxes in China was about 7.78 kg N ha⁻¹ yr⁻¹, and the fluxes of NO_2 , HNO_3 , NH_4^+ , NO_3^- , and NH_3 were estimated to be 0.67, 1.15, 0.28, 0.07 and 5.61 kg N ha⁻¹ yr⁻¹, respectively (Jia *et al.*, 2016). Furthermore, North China, East China, and Central China were subjected to higher dry deposition N fluxes in China, which accompanied with a significant increase at the rate of 1–2 kg N ha⁻¹ yr⁻¹ in the past decade (Jia *et al.*, 2016). China was not only the country with high dry N deposition fluxes but also the country with the greatest increase in dry N deposition fluxes over the past decade, where was expected as the most hotspots of N deposition. Large NO_x and NH_3 emissions resulted in the ongoing high N deposition in this region (Jia *et al.*, 2016).

4.5.3 Mechanisms responsible for effects of atmospheric N deposition on soil greenhouse gas fluxes in the forest and grasslands

Terrestrial soils are the source or sink of atmospheric CO_2 , CH_4 , and N_2O , and are suscepti-

ble to exogenous nitrogen inputs such as atmospheric nitrogen deposition. This thereby influences the regional and global carbon budget in terrestrial ecosystems (Liu and Greaver, 2010). The responses of soil greenhouse gas fluxes to N addition depend on the initial status of terrestrial ecosystems as well as the type and dose of N addition (Fang *et al.*, 2014a). Oxidized NO_3^- and reduced NH_4^+ inputs contrastingly affect soil greenhouse gas exchange fluxes. The promotion or inhibition on soil greenhouse gas fluxes are stronger from NH_4^+ -N fertilizer addition than from NO_3^- -N fertilizer addition (Jiang *et al.*, 2010; Fang *et al.*, 2012; Wang *et al.*, 2014). Also, the responses of soil greenhouse gas fluxes to N addition dose exhibit a nonlinear curve. Low dose of N addition inhibits soil CO_2 and N_2O emissions, but promotes soil CH_4 uptake, whereas high doses of N inputs have contrary effects. Overall, these contrasting responses depend on the different stage of N saturation in terrestrial ecosystems (Fang *et al.*, 2012, 2014; Xu *et al.*, 2014). Furthermore, the environmental mechanisms driving the responses of soil greenhouse gas fluxes in the northern and southern forests of China to N enrichment are contrasting. Southern forests are mainly regulated by soil NO_3^- -N content, while northern forests are controlled by the combination of soil water and NO_3^- -N contents (Li *et al.*, 2015). As far as microbial mechanisms are concerned, soil microbial communities in the northern forests use mainly high energy soil substrates, but those of subtropical forests equivalently use various soil substrates. The difference in microbial resource utilization tactics dominates the spatial pattern of soil heterotrophic respiration (Rh), and the tradeoff between root autotrophic respiration (Ra) and Rh responded contrastingly to N addition determines the interannual variability of responses at the site scale (Fang *et al.*, 2014b; Wang *et al.*, 2015). In addition, N addition increases soil ammonia-oxidizing archaea (AOA) abundance, and does not change soil ammonia oxidizing bacteria (AOB) activity. The negative and positive relationships between soil AOA abundance and CH_4 uptake and between soil AOA abundance and soil N_2O emissions are often observed, suggesting changes in soil ammonia-oxidizing bacteria community structure can well explain the fluctuation between soil CH_4 uptake and N_2O emission (Wang *et al.*, 2016).

4.5.4 Riverine carbon and nitrogen transport fluxes in Chinese terrestrial ecosystem and its impact on carbon cycle in coastal ecosystem

Rivers closely link carbon, nitrogen, water exchange between terrestrial and oceanic ecosystem, so riverine carbon, nitrogen, water exported flux monitor significantly impact on C and N biogeochemical process and associated couple at horizontal scale (Gao *et al.*, 2013). The annual discharge of runoff and sediment from river systems to ocean bodies in China reaches up to $1.49 \times 10^{12} \text{ m}^3$ and $1.72 \times 10^9 \text{ t}$, respectively, wherein the runoff discharged into the East China Sea is the highest, approximating to $1.2 \times 10^9 \text{ t}$ (MWR, 2011a, b). Based on integration analysis on runoff and C transport in main Chinese rivers, the annual C transport from the river systems to coastal ecosystem bodies in China is 64.35 TgC, wherein the Yangtze River, Yellow River, and Pearl River in China contribute 76.9% of the total C transport in China. The Yellow River and the Yangtze River transport 21.71 TgC and 16.3 TgC annually, accounting for 33.7% and 25.3% of the total annual C transport in China, respectively (Gao *et al.*, 2015; Zhu *et al.*, 2012).

Although many research reports on the effect of N on C cycle in coastal ecosystem (Doney *et al.*, 2007), there are few reports on C and N transport flux from river-ocean scale and elucidating its C and N coupling relationship. Based on C/N ratio in aquatic ecosystem,

Gao *et al.* (2015) estimate the effect of N export on C cycle in aquatic ecosystem. The results showed that the main forms of N discharged into Chinese coastal waters was NO_3^- and annual net N export from Chinese rivers reaches $12\text{--}15 \times 10^8 \text{ kg N. yr}^{-1}$, which constitutes 80% of the total of nutrient discharged into Chinese coastal ecosystem. Further estimation demonstrated that N transport flux from Chinese terrestrial ecosystem may account for 11% of the inorganic C exchange in air–sea interface (Gao *et al.*, 2015). In the future, as to carbon, nitrogen, water coupling cycle in Chinese terrestrial ecosystem, we should strengthen monitoring on carbon, nitrogen, water horizontal export flux and external N and P transport, which would be helpful to exactly estimate C budget in Chinese terrestrial ecosystem and elucidate the effect of river on carbon, nitrogen, water coupling cycle in terrestrial ecosystem.

4.6 Spatial pattern of carbon budget in China's terrestrial ecosystems

4.6.1 Carbon budget in Chinese terrestrial ecosystems based on carbon cycle model

The approaches of carbon cycle model, as an important tool in C cycle research, play a vital role in regional C budget assessment. Using the carbon flux data measured by eddy covariance, the C models involving the optimized parameters have been developed to assess the spatio-temporal patterns of different components of C budget in China. Our findings showed that annual GPP ranged from $4.42 \text{ Pg C yr}^{-1}$ to $6.03 \text{ Pg C yr}^{-1}$ in China (Yu *et al.*, 2013c), while the values of annual NPP were between 1.43 and $1.43 \text{ Pg C yr}^{-1}$, with an average of $2.83 \pm 0.83 \text{ Pg C yr}^{-1}$ (Gao *et al.*, 2012). Annual NEP resulting from the models was approximately $0.18 \pm 0.18 \text{ Pg C yr}^{-1}$, which ranged from 0.063 to $0.57 \text{ Pg C yr}^{-1}$ (Yu *et al.*, 2013c).

4.6.2 Carbon budget in Chinese terrestrial ecosystems based on the field investigated data

Field-investigated data are very important to evaluate the C budget in terrestrial ecosystems. In the past years, we integrated the multi-resource data, including long-term monitoring data and publicly published data to find that the stocks of soil organic carbon (SOC) and soil inorganic carbon (SIC) in 0–100 cm soil layer were 93.9 and 61.2 Pg C , respectively. It was estimated that vegetation C storage was about 14.9 Pg C , including 7.8 Pg C in forest vegetation, 2.1 Pg C in grassland vegetation, 3.4 Pg C in shrub vegetation, 0.95 Pg C in farmland vegetation, 0.49 Pg C in desert vegetation, and 0.25 Pg C in wetland vegetation. Furthermore, the carbon sink was estimated as $0.14\text{--}0.18 \text{ Pg C yr}^{-1}$, with an average of $0.16 \text{ Pg C yr}^{-1}$ (Yu *et al.*, 2013c). With the development of forests, Chinese forests have a huge potential to sequester C from atmosphere (Liu *et al.*, 2014), because most forests were young forest and forest age was averaged as 29 years. Under the scenarios of mature forests and with constant forest area, the C sequestration potential for vegetation and soil were 10.81 and 5.01 Pg C in Chinese forests, respectively (Wen *et al.*, 2016).

4.6.3 Carbon budget in Chinese terrestrial ecosystem based on biogeographical statistics

Based on the understanding about the influences of annual mean air temperature and annual precipitation on the spatial variations of GPP, RE, NEP, and soil respiration (RS) (Yu *et al.*, 2013b), researchers developed the approaches of biogeographical statistics on the C fluxes in China to quantify their magnitudes and spatial distributions (Yu *et al.*, 2010; Zhu *et al.*,

2014). The results showed that Chinese climate-potential GPP, NEP, RE, and RS in the 2000s were 7.78, 1.71, 6.05, and 3.96 Pg C yr⁻¹, respectively, which accounted for 4.45%–7.04%, 8.14%–11.40%, 5.87%–6.30%, and 4.93% of the global corresponding fluxes (Yu *et al.*, 2010; Zhu *et al.*, 2014). Furthermore, the whole China was considered as a regional biome-society system to assess its C sink on the basis of multi-source data integration (Zhu *et al.*, 2014; Wang *et al.*, 2015). The results demonstrated that C sink in China was about 0.41 ± 0.12 Pg C yr⁻¹ (Wang *et al.*, 2015). It is necessary to say that the C emission resulting from human disturbance can consumed 42.65% NEP in China (Wang *et al.*, 2015). Therefore, further study should emphasize the importance of reasonable ecosystem management, which may reduce the C emissions by human activities and lengthen the residence time for the fixed C in ecosystems (Wang *et al.*, 2015).

5 Prospect and emphases of ChinaFLUX coordinated observation on terrestrial ecosystem carbon, nitrogen and water fluxes

Through ten years development, ChinaFLUX innovatively established the terrestrial ecosystem carbon, nitrogen and water fluxes coordinated observation system, and made important progress in flux observation technology development, ecosystem carbon, nitrogen, water exchange processes and environment control mechanism research, model simulation, and regional carbon, nitrogen and water budget assessment. As entering the new big science and big data era, ChinaFLUX will face more challenges from many aspects of science and technology.

The future major missions of terrestrial ecosystem carbon, nitrogen, water fluxes coordinated observation and research of ChinaFLUX include: (1) achieve CO₂, H₂O, CH₄, CO, NO, NO₂, N₂O, NH₃ and HNO₃ multiple types of carbon, nitrogen, water trace gas fluxes integrated observation, so as to improve and upgrade the technical level of multiple trace greenhouse gas fluxes observation; (2) effectively organize the network observation and improve the spatial representativeness of observational sites, so as to provide services for ecosystem and global change science research; (3) develop the ground-based and space-based integrated observation system, so as to better evaluate the ecosystem carbon source / sinks and environmental response; (4) meet the data requirements of the large-scale, quantitative, predictable and early warning ecological research in the new era. Future ecological research in China are expected to be based on ChinaFLUX, to realize the leap from the ecological factors observation to the whole ecosystem observation, to develop ecological observation satellites, to improve and optimize ecosystem model system, so as to provide better services to the quantitative assessment, scientific prediction, scenario forecast and ecological early warning for the global sustainable development.

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